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Stress testing with multi-faceted liquidity: the central bank collateral framework as a financial stability tool

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Abstract

The paper studies the central bank collateral framework and its impact on banks' liquidity under an adverse stress test scenario. We construct a stress test model that accounts for a granular and multi-faceted representation of the liquidity of marketable and non-marketable assets. In particular, the model analyses banks' strategic decisions to mobilise assets through four funding channels: unsecured loans, asset sales, private repurchase agreements, or Central Bank lending. We test three scenarios: the EBA regulatory stress test exercise, a shock to Russia and the Eastern European countries, and a shock to the Southern European countries. Results show that illiquidity can trigger insolvency and that liquidity adjustment can last significantly after the initial shock. We find evidence of a threshold in the benefits of expanding the collateral framework and highlight the heterogeneous effects across different jurisdictions and financial institutions. We find that bank equity losses are reduced in aggregate up to 17% at the tail of the loss distribution and on average by around 5% when financial institutions can rely on the collateral framework channel.

Keywords: Central Bank Collateral Framework, Lender-Of-Last Resort, Asset liquidity, Collateral, Stress test

JEL classification: C63, E52, G01, G28

Non-technical summary

In times of distress, refinancing operations play a fundamental role in monetary policy transmission, granting market stabilisation and providing ample liquidity to financial intermediaries, eventually supporting the credit provision to the real sectors.[1] Therefore, the modelling of refinancing operations should not only consider the settled interest rate, the issued volumes and the auction design. Since credit to financial institutions is provided against collateral, the features of the required guarantees are also a key element to consider.

The Central Bank's collateral framework (CBCF) is the system of rules through which central banks define the characteristics of eligible collateral. The regulation includes fundamental information on the criteria for collateral eligibility, the methodology used to evaluate assets, and the computation of the haircuts applied to assets after the evaluation. The accepted assets and transactions conditions significantly modify the levels of liquidity provision to the financial system, eventually affecting the size of banks' liquidity buffers relative to their short-term liabilities[2]. The CBCF, therefore, plays a primary role in shaping the maturity mismatch between short-term debt and medium/long-term loans. Therefore, a granular representation of balance sheet characteristics becomes more relevant as including or excluding a particular class of assets in the collateral framework (or changing the associated haircuts) radically transforms the liquidity landscape and access to funding.

The present analysis extends previous studies, which attempt to provide a quantitative setting to inform the debate on the appropriateness of the CBCF scope (Ashcraft et al., 2011; Bindseil et al., 2017b; Bindseil and Lanari, 2022). We add in particular to the stream of models that design explicitly the features of the CBCF coupled with a sensible representation of the regulated financial systems and its main building blocks, i.e. (i) the assets variety in terms of scope of the investments or liquidity, (ii) the heterogeneity of the banks operating in the markets with diverse business models, and (iii) the different strategies to deal with financial shocks and market distress.

Building on Cont and Schaanning (2017a, 2019) and Cont et al. (2020), we introduce a model where shocks to assets values induce endogenous liquidity shortfalls to which banks respond using four diverse financing sources: asset sales, unsecured credit, repo credit or Central Bank credit. Such an extension defines multiple interactions in the solvency-liquidity landscape, leading to the amplification of exogenous shocks.

We propose two applications of the model. The first is based on a simulated finan-

[1] See e.g. Hutchinson et al. (2020); Lane (2020) for the case of the Eurosystem during the COVID19 crisis.

[2] On this regard, recall that insufficient buffers relative to short-term liabilities have been pointed to be a trigger of the GFC, and one of the primary causes of an (at least temporarily) excessive reliance on Central Bank funding (BCBS, 2013).

cial system with banks and investors/depositors, where balance sheets are simulated in line with the empirical analysis by Farnè and Vouldis (2021). Next, we present an application on empirical data using the Financial Information Reporting (FINREP) framework, which includes information on balance sheets, income statements and equity, financial assets and liabilities at the bank level, and AnaCredit, which integrates the granularity of exposures to non-financial corporations. We test the effect of a collateral framework expansion on the financial system's exposure to bank-specific and systemic losses. Then we compare the outcomes of stress tests in two cases: one in which banks have access to multiple channels and, in particular, to credit-upon-collateral to deal with liquidity and asset values shock, the other in which the only available strategy is to sell assets at endogenously determined market prices. We find, in particular, that:

- while homogeneous expansions of the collateral framework have a significant impact on equity losses, the benefits do not increase linearly with the magnitude of the widening yet become stationary after a certain threshold in haircut reduction;
- bank equity losses are reduced in aggregate up to 17% at the tail of the loss distribution and on average by around 5% when financial institutions can rely on the collateral framework channel

The collateral framework of the ECB has been the object of a lively debate involving central bankers and practitioners discussing the appropriateness of its scope and the principles and objectives of monetary authorities (Calomiris et al., 2016; Nyborg, 2016; Bindseil and Laeven, 2017). To inform the debate, we find evidence of the collateral framework's heterogeneous and non-linear risk-mitigating effects for both the simulated and the empirical applications.

There are several ways to extend the present study. For instance, while we model constant haircuts for assets and the repo market, haircuts might change during a crisis. Similarly, we obtain conservative estimates for the shocks mediated by price contagion since the market impact of asset sales is modelled through a linear pricing function. However, non-linearity could be tested to fit closer the price reactions in periods of distress (see e.g. section 3.2 in Cont and Schaanning, 2017a, for a discussion). Lastly, the analysis focuses on indirect contagion entailed by the overlap of portfolio exposures between banks and does not analyse possible second-round effects due to bank defaults. We discuss such restrictions throughout the paper and leave possible extensions to further research.

1 Introduction

1.1 Relevance of the collateral framework in stress tests

The Global Financial Crisis (GFC) of 2007-08 highlighted the importance of bank intermediation in maintaining the pressure on the financial system at sustainable levels in times of distress. During the last decades, to support the financial institutions in the achievement of their intermediation outcomes, Central Banks fine-tuned conventional monetary policy, introduced unconventional measures, and complemented their policy toolkit with liquidity regulations and capital standards enforced by supervisory authorities.

More recently, the global macroeconomic shock following the outbreak of the Covid 19 pandemic has put through the winger the complete set of precautionary measures and their effectiveness in mitigating financial distress: in a context of severe dislocation of the financial markets (Zhang et al., 2020; Albulescu, 2021; Gubareva, 2021), involving even the most liquid segments (Ziemba, 2020; Zaremba et al., 2021; Kargar et al., 2021; Zaremba et al., 2022), Central Banks across the world undertook actions that outpaced the previous responses to the GFC both in scope and size aiming at maintaining continuous access to liquidity and favourable credit conditions to the private sector (English et al., 2021; Cantú et al., 2021). Flourishing literature studied both theoretically and empirically the role of monetary channels, trying to measure their impact once taken singularly, see e.g. Altavilla et al. (2014) Levin and Sinha (2020), Moessner and de Haan (2022), Altavilla et al. (2015) and Aguilar et al. (2020), or assessing their joint effectiveness (Curdia and Woodford, 2011; Popoyan et al., 2017; Altavilla et al., 2019; Bernanke, 2020; Wei and Han, 2021) with a particular focus on non-standard (or unconventional) policies (Altavilla and Giannone, 2017; Bhar and Malliaris, 2021).

Despite adopting diverse methodologies, the extant literature does not always emphasise certain aspects of refinancing operations. Such policies have proven to be fundamental for monetary policy transmission, granting market stabilisation and providing ample liquidity to financial intermediaries, eventually supporting the credit provision to the real sectors (see e.g. Hutchinson et al., 2020; Lane, 2020, for the case of the Eurosystem during the Covid-19 crisis)). When considering refinancing operations, especially, their modelling should not only consider the settled interest rate, the volumes effectively issued and the auction design. Since credit to financial institutions is provided against collateral, the features of the required guarantees are also a key element to consider. The Central Bank's collateral framework (CBCF) is the system of rules through which central banks define the characteristics of eligible collateral.[3].

[3] See e.g. Chailloux et al. (2008) for a general review.

The rules include fundamental information on the criteria for collateral eligibility, the methodology used to evaluate assets, and the computation of the haircuts applied to assets after the evaluation[4].

The assets accepted and the conditions of the transactions significantly modify the levels of liquidity provision to the financial system, eventually affecting the size of banks' liquidity buffers relative to their short-term liabilities[5]. Indeed, while actively contributing to the maturity transformation in financial markets, banks keep unbalanced the ratio between short-term debt and medium/long-term loans to the real economy. Such a mismatch poses a trade-off between the efficiency of the banking system in delivering maturity transformation and financial stability.[6] The degree of such a maturity mismatch links directly to financial stability and the composition of the long-term investments at both aggregate and bank-specific levels.

Within this framework, CBCFs become more relevant as they interact with the granular characteristics of the balance sheets of the financial institutions populating the banking system. Including or not a particular class of assets in the collateral framework (or changing the associated haircuts) radically transforms the liquidity landscape and the access to funding sources of financial intermediaries. For this reason, the definition and calibration of the collateral frameworks are among the most complex and economically significant elements of monetary policy implementation (Bindseil et al., 2017a) and played a relevant role in the last decade and during the COVID-19 crisis (see the scope and the amount of the used collateral as in Fig. 1). Non-coincidentally, the collateral framework of the ECB has been the object of a lively debate involving central bankers and practitioners discussing the appropriateness of its scope concerning the principles and the objectives of the monetary authorities (Calomiris et al., 2016; Nyborg, 2016; Bindseil and Laeven, 2017). The present analysis extends, therefore, previous studies, which attempted to provide a quantitative setting to inform such a debate (Ashcraft et al., 2011; Bindseil et al., 2017b; Bindseil and Lanari, 2022). We add in particular to the stream of models that design explicitly the features of the CBCF coupled with a sensible representation of the regulated financial systems and its main building blocks, i.e. (i) the assets variety in terms of scope of the investments or liquidity, (ii) the heterogeneity of the banks operating in the markets with diverse business models, and (iii) the different strategies to deal with financial

[4] Generally, an throughout this paper, a haircut refers to a parameter $h \in [0, 1]$ such that the value v of an asset is discounted to $\overline{v} = (1 - h)\, v$.

[5] On this regard, recall that insufficient buffers relative to short-term liabilities have been pointed to be a trigger of the GFC, and one of the primary causes of an (at least temporarily) excessive reliance on Central Bank funding (BCBS, 2013).

[6] "[T]here is a trade-off to be struck. Increased maturity transformation delivers benefits to the non-bank sectors of the economy and produces term structures of interest rates more favourable to long-term investment. But the more significant the aggregate degree of maturity transformation, the more the systemic risks and the greater the extent to which risks can only be offset by the potential for Central Bank liquidity assistance." (Turner, 2009)

shocks and market distress.

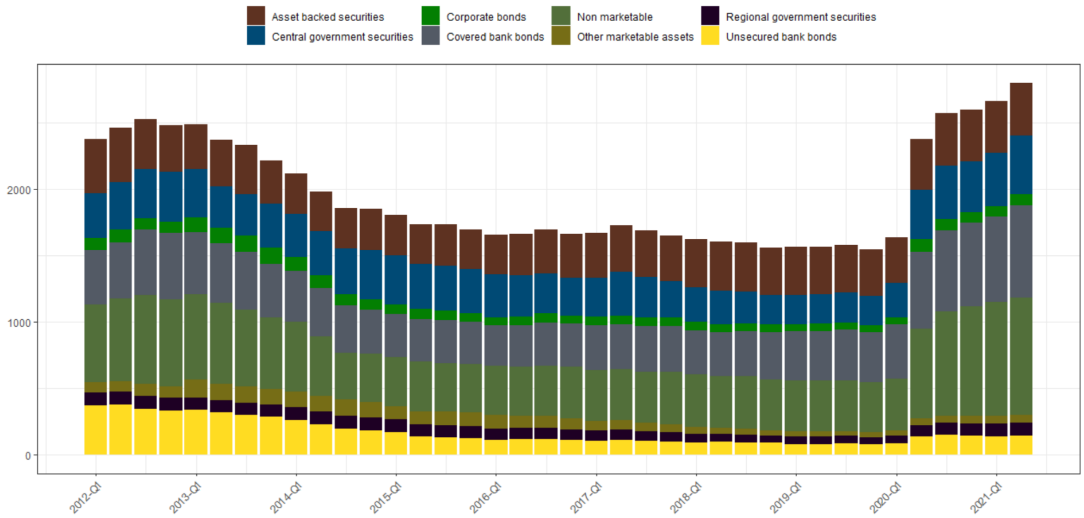


Figure 1: Types and amounts of used collateral for the ECB credit operation from Q1 2012 to Q2 2021. Authors' calculations on publicly available aggregate data available at `https://www.ecb.europa.eu/paym/coll/charts/html/index.en.html`.

1.2 Contributions of the paper

On the background of previous studies, the model adds to the literature a stress test model targeted to analyse the role of the central banks' collateral framework as it emerged during the last decade. Building on Cont and Schaanning (2017a, 2019) and Cont et al. (2020), we introduce a model where shocks to assets values induce endogenous liquidity shortfalls to which banks respond using diverse financing sources: asset sales, unsecured credit, repo credit or Central Bank credit. Such an extension defines multiple interactions in the solvency-liquidity landscape, leading to the amplification of the exogenous shocks prompted as the starting point of the stress test.

The integration and the enhancement of Cont and Schaanning (2017a) and Cont et al. (2020) allow us to account for multiple sources of loss amplification (or dampening) whose intertwined effects constitute the significant aspects of novelty of the proposed model. In particular, our model extends the following features of previous studies:

1. **Multiple liquidity categorisation.** The model relies on two intertwinings (but not identical) extensive asset liquidity categorisation: the one defined by the parameters of the collateral framework and the one implied by the market depths, enriching the constant haircut approach (Cont et al., 2020) and constant market depth approach (Greenwood et al., 2015). This joint framework provides a flexible analytical context to test how individual bank positions or

systemic stress outcomes respond to modifications of the collateral framework's parameters.

2. **Banks liquidity strategies.** The inclusion of multiple funding sources to deal with assets' value shock and liquidity shortfalls opens the issue of the strategic behaviours of financial institutions. First, it is shown how the complexity of the strategic landscape makes unlikely any global maximisation approach by the agents since an optimal, or preferred, liquidity stress strategy (LSS) (adapting the definition of Bindseil et al., 2017b) does not exist or is ill-defined in a context of multiple funding sources with endogenous costs determination. Second, extending Coen et al. (2019), we encode the effects of regulatory ratios as signals and practical requirements to prevent liquidity shortfall or access to different funding sources.

3. **Systemic effects due to common asset holdings.** Indirect contagion is transmitted through an implicit network defined using common asset holdings based on the bank's exposure classification. This way, institutions recurring to fire sales to gather liquidity might induce losses on other agents in the financial markets through price-mediated impact and mark-to-market balance sheet losses.

4. **Solvency-liquidity interaction channels.** Within a coherent solvency-liquidity interplay, liquidity shocks are endogenously generated by funding shortfalls linked to the deterioration of banks' fundamentals. The approach does not require the introduction of exogenous liquidity shocks, allowing instead to test whether i) shocks to a single asset class induce heterogeneous liquidity stress according to institution-specific balance sheet characteristics[7]; ii) the impact of different starting shocks on single financial institutions from a systemic perspective.

We propose two separate applications of the models. The first one is operating on a simulated financial system with banks and investors/depositors, where balance sheet typical values are simulated on the line of the empirical analysis by Farnè and Vouldis (2021). The simulation allows specifying four bank business models, operating in a market with discrete asset categories diversified in market depths, Central Bank haircuts and private repo haircuts. Next, we present an empirical application. Our framework suits an empirical decomposition of the balance sheets of the Eurosystem banks based on integrating multiple data sources. The balance sheets of banks are recovered using the Financial Information Reporting (FINREP) framework, which includes information on balance sheets, income statements and equity, financial assets

[7] This enriches the widely adopted framework of homogeneous cash inflows/outflows of ECB liquidity stress tests.

and liabilities at the bank level[8]. Moreover, the information on balance sheets is integrated by expanding the granularity of the exposures to non-financial corporations through AnaCredit. The scope of AnaCredit covers loans to companies harmonised across member states. Given the balance sheet representation, the single asset categories are then associated with category-specific market depths computed from publicly available information on transaction volumes and market volatilities (as in Cont and Schaanning, 2017a; Coen et al., 2019), and the information on haircuts from the public Eligible Assets Dataset available at the European Central Bank.

With the above applications, we first test the effect of a collateral framework expansion on the financial system's exposure to bank-specific and systemic losses. Next, we compare the outcomes of stress tests in two cases: one in which banks have access to multiple channels and, in particular, to credit-upon-collateral to deal with liquidity and asset values shock, and the other in which the only available strategy is to sell assets at endogenously determined market prices. In this respect, for both applications, we confirm the intuition on the risk-mitigating effects of the collateral frameworks. However, we highlight that i) while homogeneous expansions of the collateral framework have always a significant impact on equity losses, the benefits do not increase linearly with the magnitude of the widening, yet become stationary after a certain threshold in haircut reduction; ii) in the empirical application to the European Banking system we quantify the reduction of the systemic losses, finding that relative systemic losses estimates in a stress test are reduced up to 17% in the most severe scenarios and on average are of around 5% when the financial institutions can rely on the collateral framework channel.

1.3 Relevant literature

Our contribution relates to three main branches of the literature. First, we refer to the literature on stress testing and financial stability. We model in one framework several properties of two classes of stress tests. We include the price-mediated effects of fire sales through correlated exposures (see Shleifer and Vishny, 2011, for a review on fire sales), studying the induced losses and eventually the impact on the systemic stress as in (Cont and Schaanning, 2017a; Coen et al., 2019) and the mitigation effect of the collateral framework. We also represent the multiple funding sources of financial institutions and the possible liquidity shortfall induced by credit-sensitive investors as in Cont et al. (2020), yet relaxing the hypothesis on the pecking order of the available mitigating strategies and giving a more realistic picture of the collateral framework.

[8] Entities reporting to FINREP in our dataset include investment companies, banks and banking groups in the European Union subject to the Capital Requirements Directive IV (CRD IV). More on FINREP can be found here: `https://www.bankingsupervision.europa.eu/banking/statistics/html/index.en.html`.

Moreover, we relate the banks' actions to the regulatory requirements as in Coen et al. (2019).

Second, we enrich and extend the theoretical works modelling the Central Bank collateralised credit operations. Our model improves upon Bindseil et al. (2017b) and Bindseil and Lanari (2022), introducing a realistic framework designed to relax the continuous liquidity hypothesis and explore the dynamics of the liquidity crisis in a setting with boundedly rational heterogeneous banks and depositors. This framework allows us to factor in the effects of the regulatory constraints on banks' asset liquidation strategies and, hence, better represent their liability structure, exploring the impact of the collateral framework calibration on a financial system populated by banks operating under different business models. Other classical models relevant to this paper are Rochet and Vives (2004) modelling fire sales and Central Bank collateral in a stylised two-asset world and the general multiple funding equilibrium literature, as reviewed in Morris and Shin (2006). Relatively recent literature integrates Central Bank credit into macroeconomic models (Gertler and Kiyotaki, 2015; De Fiore et al., 2018). These contributions link bank runs to the Central Bank's monetary policies in a general equilibrium framework[9] with continuous liquidity and *ad hoc* assumptions on the limits to maturity transformation for the banking system (Ashcraft et al., 2011). In that context, haircuts affect the leverage ratio, eventually influencing the costs of assets and the shadow cost of equity: the financing costs are endogenously derived. At the same time, banks and other agents are not heterogeneous. The inclusion of the collateralised credit within a set of available macroprudential policies has also been studied in some agents based models (ABMs), see, e.g. the rich framework outlined by Popoyan et al. (2020) whereby, however, the collateral accepted in Central Bank's credit operations is limited to central government bonds.

Lastly, we contribute to the existing empirical works that focus on the banks' strategic recourse to Central Bank credit triggered by exceptional policy measures during a crisis and regular times (Berger et al., 2017; Cassola and Koulischer, 2019; Drechsler et al., 2021). We offer, in particular, a theoretical perspective in designing a framework whereby the effects of the haircuts broadening or tightening can be tested in a policy scenario analysis. The model allows drawing some preliminary conclusions on the bank lending channel of monetary policy Jiménez et al. (2012, 2014) and the effects of unconventional monetary policies when the interest rate approaches negative territories (Rodnyansky and Darmouni, 2017; Altavilla et al., 2021; Heider et al., 2019).

[9] The authors model asset liquidity as a continuum yet adopting an analogous artefact to represent the banks and impose heterogeneity gauging on the distributional properties of banks parametric features, rather than sketching heterogeneity in terms of strategies and business models.

1.4 Outline

The rest of the paper is organised as follows. Section 2 presents an operational model for stress-testing a financial system where banks have access to multiple funding sources, including the Central Bank collateral framework. Section 3 analyses the properties of the framework and discusses the banks' allocation strategies in the liquidity market. In Section 4 we describe the data used for the Euro Area banks, and Section 5 presents our empirical results. Section 6 concludes the article with a final remark.

2 Multi-faceted liquidity in a stress test model

We consider an operational model with N_B financial institutions (or banks)[10]. The proposed balance sheet representation distinguishes between marketable and non-marketable assets, encumbered and unencumbered assets. The section outlines the technical characteristics of the model in the following order: i. the banks' balance sheet composition, ii. the definition of the shocks, iii. banks' liquidity strategies, and iv. the timeline of the model.

2.1 Banks' balance sheet

Let us consider K_M marketable asset classes and K_N non-marketable asset classes. We denote the set of asset holdings of bank i as $A^M_{i,\mu} = A^{M,enc}_{i,\mu} + A^{M,une}_{i,\mu}$ for encumbered and unencumbered marketable assets ($\mu = 1, \ldots, K_M$), and $A^N_{i,\nu} = A^{N,enc}_{i,\nu} + A^{N,une}_{i,\nu}$ for encumbered and unencumbered non-marketable assets ($\nu = 1, \ldots, K_N$). Each of these asset categories is endowed with two sets of asset characteristics. The first set parametrises the conditions under which a unit of an asset can be transformed into cash holdings and includes the market depths D_μ, the haircuts in the repo market h^{rp}_μ and the Central Bank haircuts $h^{M,cb}_\mu$, $h^{N,cb}_\nu$[11]. The second set includes risk weights (ρ^M_μ, ρ^N_ν) and liquidity coverage ratio (LCR) haircuts, defining the characteristic of the assets as determined by the regulatory environment[12].

The liabilities of each bank are distinguished into six categories: equity, unsecured debt, Central Bank debt, repo debt, other long-term debt and deposits. The total amount of deposits is calibrated, and their granular distribution is simulated by

[10] In the following, we will equivalently refer to banks and financial institutions. The model adapts to the possible inclusion of heterogeneous market agents regarding balance sheet composition, strategic behaviour and interaction with the regulatory environment.

[11] It will be evident in the following how these parameters enter the dynamics of the model. Market depths are supposed to measure the liquidity of the market segment associated with that specific market class and hence are related to marketable assets only. The same restriction applies to collateral that is mobilised on the repo market. Relying on related empirical studies, we assume that only marketable assets are used for repos (Schaffner et al., 2019; Julliard et al., 2019).

[12] While risk weights are defined for both marketable and non-marketable assets, only high-quality assets enter the computation of the LCR, hence h^{lcr} refers to those assets only.

Assets side			Liabilities side
$A_{\mu,i}^{M,enc}$, $A_{\mu,i}^{M,une}$	Marketable	e_i	Equity
$A_{\nu,i}^{N,enc}$, $A_{\nu,i}^{N,une}$	Non-marketable	l_i^u	Unsecured credit
c_i	Cash	l_i^{rp}	Repo credit
o_i	Other assets	l_i^{cb}	Central Bank credit
		l_i^{ot}	Other credit
		l_{ik}^d	Short-term deposits

Table 1: Balance sheet representation for bank i.

defining a population of depositors/investors. The framework allows, therefore, for a stochastic mechanism that models the differential credit sensitivity of diverse classes of fundings, e.g. retail, wholesale, institutional and deposits with agreed maturity. In addition, modelling short-term funding as an ensemble of heterogeneous depositors has the following benefits. On one side, it is possible to capture the redistribution dynamics of wealth within the financial system if the depositors can withdraw deposits and reallocate them to other banks. On the other hand, the wealth eroded because of illiquid or insolvent banks provide a valuable indicator to measure the impact of the financial shocks on depositors' wealth at a systemic level.

2.2 Assets and liquidity shocks

As in Cont and Schaanning (2017a, 2019); Coen et al. (2019), shocks to assets' values are prompted as a starting event of the stress test. Any impact on asset prices is transferred to banks' balance sheets, inducing mark-to-market losses. Formally, a vector of assets value shock is defined by

$$\left(\epsilon^M, \epsilon^N\right) = \left(\epsilon_1^M, \ldots, \epsilon_{K_M}^M, \epsilon_1^M, \ldots, \epsilon_{K_N}^N\right). \tag{1}$$

where exogenous shocks take the most general form, with ϵ_μ^M and ϵ_ν^N taking any value between zero and one. On the contrary, shocks implied by some endogenous shift in the market price apply only to marketable assets, meaning that ϵ_ν^N is necessarily set to zero. Assets value shocks, independently of their value or source, affect banks' fundamentals: the immediate losses are absorbed via equity

$$\underline{e}_i = e_i - \sum_{\mu}^{K_M} \epsilon_\mu^M A_{\mu,k}^M - \sum_{\nu}^{K_N} \epsilon_\nu^N A_{\nu,k}^N \tag{2}$$

and transfer to the leverage ratio, the capital ratio (or risk-weighted capital ratio, RWCR) and the liquidity coverage ratio (LCR)[13]

$$
\begin{aligned}
\underline{\text{LR}}_i &= \frac{e_i - \sum_{\mu}^{K_M} \epsilon_{\mu}^{M} A_{\mu,i}^{M} - \sum_{\nu}^{K_N} \epsilon_{\nu}^{N} A_{\nu,i}^{N}}{c_i + o_i + \sum_{\mu}^{K_M} (1-\epsilon_{\mu}^{M}) A_{\mu,i}^{M} + \sum_{\nu}^{K_N} (1-\epsilon_{\nu}^{N}) A_{\nu,i}^{N}} \\
\underline{\text{RWCR}}_i &= \frac{e_i - \sum_{\mu}^{K_M} \epsilon_{\mu}^{M} A_{\mu,i}^{M} - \sum_{\nu}^{K_N} \epsilon_{\nu}^{N} A_{\nu,i}^{N}}{\sum_{\mu}^{K_M} \rho_{\mu}^{M} (1-\epsilon_{\mu}^{M}) A_{\mu,i}^{M} + \sum_{\nu}^{K_N} \rho_n u^N (1-\epsilon_{\nu}^{N}) A_{\nu,i}^{N}} \\
\underline{\text{LCR}}_i &= \frac{\sum_{\mu}^{K_M} (1-\epsilon_{\mu}^{M,une})(1-h_{\mu}^{LCR}) A_{\mu,i}^{M}}{\sum_{\mu}^{K_M} \boldsymbol{\omega}^{out} \cdot \mathbf{l}_i - \sum_{\mu}^{K_M} \omega_{\mu}^{in} (1-\epsilon_{\mu}^{M}) A_{\mu,i}^{M} + \sum_{\nu}^{K_N} \omega_{\nu}^{N,in} (1-\epsilon_{\nu}^{N}) A_{\nu,i}^{N}}
\end{aligned}
\tag{3}
$$

where $\mathbf{l}_i = (l_i^u, l_i^{cb}, l_i^{ot}, l_{i,1}, \dots, l_{i,D_i})$ is the vector collecting the liabilities with the associated outflow weights $\boldsymbol{\omega}^{out}$ implied by the regulatory environment.

After a shock to the value of assets, the leverage ratio or the risk-weighted capital constraint may fall below acceptable levels and trigger the loss of credit-sensitive funding. Such funding includes, for instance, retail deposits available for withdrawal or short-term loans for which the rollover is no longer possible at acceptable market conditions. In Cont et al. (2020) this is represented as a credit downgrade implied by a fall in the leverage ratio. On the same line, we take as reference the RWCR and condition the shortfall on the leverage ratio of the bank: credit-sensitive fundings run-off if the RWCR falls below a threshold $\bar{\xi}$ and the probability of withdrawal depends on the leverage ratio.

Even though we share the core idea, admitting that depositors' runs are linked to banks' fundamentals and follow the downturn of business cycles (De Graeve and Karas, 2014; Pereira et al., 2019)[14], we nevertheless recognise that generally, investors have different run-off rates and that their variability increases during financial distress. In particular, the increased withdrawing rate also depends on coordinating the depositors' behaviours, depending on heterogeneous liquidity needs and access to the relevant information. Therefore, we model two classes of depositors that can be populated using the minimal information provided in standard balance sheets datasets: stable and informed depositors. Stable depositors do not withdraw within the stress test horizon. In contrast, informed depositors withdraw following the outcome of a stochastic variable parametrised by the leverage ratio of the bank[15]. Then, the shortfall for bank i

[13] Notice that we will refer in the following to the general notion of equity, while the capital e_i refers to Tier 1 capital in the case of the leverage ratio, while it refers to Common Equity Tier 1 in the case of the risk-weighted capital ratio. Whenever the granularity of the balance sheet information is sufficient, e_i is replaced with the correct capital classification.

[14] See Kiss (2018) for a review of the literature on the topic.

[15] The framework is designed to allow for a more extensive heterogeneity of depositors. An example is the category of ordinary depositors, stickier than informed depositors and following the lead of other agents in the same bank when deciding. We have chosen to keep the depositor classification minimal.

implied by depositors run at a given time step is:

$$\lambda_i^d = \mathbb{E}\left[\sum_{r \in D_i} l_{r,i}^d X_{r,i}\right]$$

where $X_{r,i}$ are independent Bernoulli random variables $B(p_{r,i})$ where

$$p_{r,i} = \begin{cases} 0 & \text{if} \quad \mathrm{RWCR}_i > \xi_i \\ e^{-\delta^d \, \mathrm{LR}_i} & \text{if} \quad \mathrm{RWCR}_i \leq \xi_i \end{cases} \tag{4}$$

Analogously, other liabilities, such as repo and unsecured credit, shrink due to missed rollover following

$$\lambda_i^{un} = e^{-(\delta^{un} \, \mathrm{LR}_i)} \cdot l_i^{un} \qquad \lambda_i^{rp} = e^{-(\delta^{rp} \, \mathrm{LR}_i)} \cdot l_i^{rp} \tag{5}$$

and the overall liquidity shortfall for bank i is then equal to $\lambda_i = \lambda_i^{un} + \lambda_i^{rp} + \lambda_i^d$.

2.3 Banks' strategies

Banks can undertake several actions when cash holdings are insufficient to cover the funding's outflows or, more generally, if they are willing to modify their balance sheet positions. The modelling options for these actions follow those implemented in Cont et al. (2020) with two additional features.

First, we decompose the asset universe into discrete classes uniquely identified by their market depth and private repo haircut, marketable assets, and Central Bank haircut category for marketable and non-marketable assets. This representation marks a significant difference between the extant contributions, which mainly rely on two modelling strategies: i) they rely on a one-dimensional representation of liquidity focusing, e.g. on fire sales only as in Greenwood et al. (2015) (with uniform market depths) or in (Cont and Schaanning, 2017a) and Coen et al. (2019); ii) they model multiple liquidity channels but restrict the mobilisation of collateral to a single segment of the liquidity spectrum, as in Cont et al. (2020) where the illiquid assets only are used to back up the loans from the Central Bank or as in Popoyan et al. (2020) where only government debts are pledged.

Second, we do not impose a strict pecking order of the operations since it is more likely that banks operate by selecting their strategies according to i) the effective costs of liquidity, depending on the market discounts for sales, or depending on the interest rate and the applied haircut for the inter-bank and Central Bank credit operations[16];

[16] As explained in the introduction, we generally refer to haircuts as the difference between the collateral value pledged in the bank's balance sheet and the value of the loan issued by the Central Bank. Our notion of haircut then includes any ex-ante valuation operation and any own-use or

ii) their needs and objectives, as the strategy changes if banks need to cover depositors' withdrawals or balance their asset portfolio to restyle their regulatory ratios (Kedan and Veghazy, 2021; Jasova et al., 2021).

Here, we list the equations defining the terms and conditions of each funding option together with the implications for the capital and the regulatory indicators:[17]

1. **Unsecured credit.** Banks have access to unsecured credit at an exogenous interest rate r_U. When banks want to access this segment, the volume they obtain depends on their fundamentals following the approach of Cont et al. (2020):

$$v_U = \frac{e_i\,\psi - \sum_\mu A^M_{\mu,i} - \sum_\nu A^N_{\nu,i}}{1 + r_U\psi} \tag{6}$$

where ψ is a parameter ruling the sensitivity to the banks leverage[18], r_U is the interest rate for unsecured credit, and the costs of the operation are covered via equity:

$$e_i - r_U\, v_U \ . \tag{7}$$

As for the rest, the impact on the regulatory ratios depends on the nature of the specific operation. For example, if used to replace deposits, it might impact the LCR because swapping deposits with unsecured credit changes the composition of the denominator.

2. **Liquidity through repurchase agreements.** To gather liquidity on the repo market, a bank can mobilize unencumbered collateral in exchange for a volume v_{RP} that is modulated by the haircut applied to the value of the assets provided

$$v_{RP} \ = \sum_\mu (1 - h^{RP}_\mu) A^{M,une}_{\mu,i} p^{RP}_{\mu,i} \tag{8}$$

$$e_i - v_{RP} \cdot r_{RP} \tag{9}$$

where p^{RP} is the amount of collateral mobilized in this channel and h^{RP}_μ the asset-specific private repo haircut.

3. **CB collateralized lending.** As anticipated, banks can access Central Bank credit if they hold and are ready to mobilise sufficient eligible collateral. The value of funding raised depends again on the value of the assets pledged:

$$v_{CB} = \sum_\mu (1 - h^{CB}_\mu) A^{M,une}_{\mu,i} p^{CB}_{\mu,i} + \sum_\nu (1 - h^{CB}_\nu) A^{N,une}_{\nu,i} p^{CB}_{\nu,i} \tag{10}$$

$$e_i - v_{CB} \cdot r_{CB} \tag{11}$$

foreign currency add-on.

[17] For the sake of the synthesis, we limit the explicit derivation to the equity and the leverage ratio, the formulas for the remainder can be derived accordingly.

[18] Note that since the volume of unsecured credit is constrained by the leverage the numerator of Eq. (6) contains encumbered and unencumbered assets.

where $p^{CB}_{\mu,i}$ and $p^{CB}_{\nu,i}$ are the relative amounts of marketable assets in the category μ and non-marketable assets in the category ν that are pledged, and r_{CB} is the Central Bank interest rate.

4. **Assets sales.** Banks can also opt to sell part of their disposable marketable assets. The liquidity they gather varies with the fluctuations of the market prices determining the market discounts. These eventually depend on the total volume of assets sold for any specific category and the relative market depth. Following Donier et al. (2015), Cont and Schaanning (2017a) and Coen et al. (2019), we define a linear price impact function for the price of the asset μ:

$$\Delta_\mu = \frac{\sum_j s^M_{\mu,j} A^{M,une}_{\mu,i}}{D_\mu} \tag{12}$$

where $s^M_{\mu,j}$ is the relative quantity of assets in the category μ that bank j decides to sell. Once established that only marketable assets enter the dynamics of assets sales, we omit the suffix M for $s^M_{\mu,j}$ to keep the notation lighter.

Price shifts induce a loss via two different channels. First, while liquidating sellers accept the given market price and face an overall value reduction equal to:

$$\text{Dis}_{\mu,i} = \alpha \underbrace{A^{M,une}_{\mu,i} s_{\mu,i}}_{\text{Sold unencumbered assets}} \frac{\sum_j s_{\mu,j} A^{M,une}_{\mu,j}}{D_\mu} \tag{13}$$

The coefficient α obtains the price impact as an average over the liquidation horizon. Standard values are $\alpha = \frac{1}{2}$ and $\alpha = 1$, the former assumes that assets are liquidated with success uniformly over the liquidation horizon. At the same time, the latter re-factors price impacts as if all the assets were sold at the final price. Second, all financial institution needs to register balance sheets with mark-to-market losses mediated by market price to their remaining holdings

$$\text{Mtm}_{\mu,i} = \underbrace{\left(A^{M,enc}_{\mu,i} + A^{M,une}_{\mu,i}\right)(1 - s_{\mu,i})}_{\text{Remaining assets}} \left(1 - \frac{\sum_j s_{\mu,j} A^{M,une}_{\mu,j}}{D_\mu}\right) \tag{14}$$

In the actual implementation of the model, the first loss is registered coincidentally to the sale process, while the second is prompted as an asset shock as in Eq. 1. The overall collected cash is then

$$v^\mu_S = \alpha A^{M,une}_{\mu,i} s_{\mu,i} \left(1 - \frac{\sum_j s_{\mu,j} A^{M,une}_{\mu,j}}{D_\mu}\right)$$

and the impact on equity

$$\underline{e}_i = e_i - \sum_{\mu}(1-(1-\alpha)s_{\mu,i})A_{\mu,i}\frac{\sum_j s_{\mu,j}A^{M,une}_{\mu,j}}{D_\mu} \tag{15}$$

2.4 Model's timeline

With the given setup, we implement the following timeline:

i. A shock as per Eq. 1 hits the value of assets, and the banks register the induced losses to the balance sheets. As a result, banks' fundamentals (LR, LCR, RWCR) change accordingly.

ii. Sensitive depositors or other lenders respond to the fundamental changes. At this step, the shock may trigger a partial loss of funding due to deposits coordinated withdrawal or missed rollover on the part of the repo or unsecured debt. This defines the bank-specific liquidity shortfalls λ_i $(i = 1, \ldots, N_B)$.

iii. All the banks in the financial system are called to action. Initially, they deal with liquidity shortfalls or use the available funding source to restore the possibly deteriorated fundamentals (LR, RWCR and LCR). Both the issues are faced recurring to the funding sources described above. First, banks seek liquidity through unsecured lending and then choose a strategy to mobilise or sell their collateral, exploiting the various channels according to their objectives and collateral availability.

iv. The undertaken mitigating actions affect the economic environment. In particular, sales affect asset market prices. This change occurs because market participants sell at the price they get from the market (see Eq. (13)).

v. Once the banks have implemented their strategies, the liquidity and solvency of each financial institution are assessed: banks that are not able to cover the liquidity shortfall default for illiquidity, banks that, after repaying, cannot face the costs of the compensating borrowing and operate with negative equity default for insolvency[19].

vi. The mark-to-market losses mediated by asset prices (eq. (14)) are transferred to banks' balance sheet items in the form of assets value shock as in step 1. The cycle closes and restarts.

With respect to the timeline and its graphical representations in Figure 2, we provide three clarifying comments. First, a single round of timeline, from point (i) to

[19] The inability to restore liquidity and capital indicators to acceptable levels is not a cause of bankruptcy.

point (vi), is to be considered as a process at the weekly time scale. Thus, the model horizon depends on the number of repetitions of the round that defines the timeline and in our proposed applications, with 10 repetitions, it ranges between two to three months. Second, with the model's main equations, we outline an interaction between balance sheet variables and the fundamental indicators derived from them. These indicators are usually updated and published annually, and under current regulations in the European Union, they become binding at this frequency. Nonetheless, they can serve as indicators of the liquidity and solvency conditions of financial institutions to informed and sensitive investors. For this reason, the updated indicators do not directly affect the conditions of financial institutions, but rather, they interact with the environment, either restricting or expanding the possibility of accessing unsecured credit or triggering the withdrawal of credit-sensitive funding. Finally, we note that the graphs in Figure 2 generalize the similar diagrams of Cont and Schaanning (2017a) and Cont et al. (2020), with two relevant differences concerning the actions of banks. In our framework, the position in the leverage diagram changes depending on the channel used by the bank to restore its position and can result in multiple outcomes (see the connections from C to D1, D2, D3). This broadens the potential for active balance sheet changes in comparison to Cont and Schaanning (2017b) and Coen et al. (2019), where the trajectories in the leverage diagram must always be linked to a reference value for a complex dynamic. The position in the liquidity-solvency diagram, moreover, evolves in a nonmonotonic manner due to the non-hierarchical and unordered access to channels by banks, unlike the hierarchical and ordered access in Cont et al. (2020).

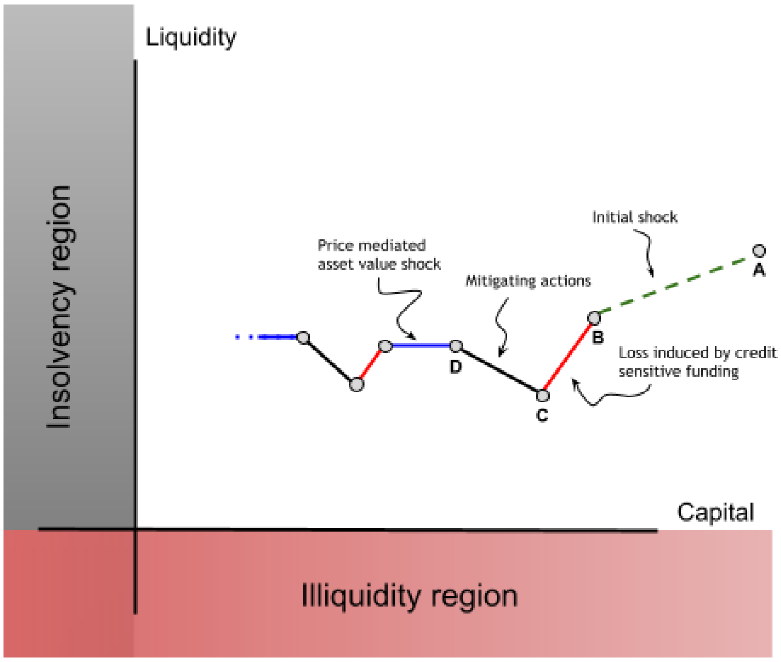
3 A simulated financial systems of heterogeneous banks

We apply the model to a simulated financial system populated by heterogeneous banks and depositors. The approach is common in previous stress test models (see e.g. Cont and Schaanning, 2019; Cont et al., 2020) and it is intended to give a theoretical overview of the model properties in a controlled environment.

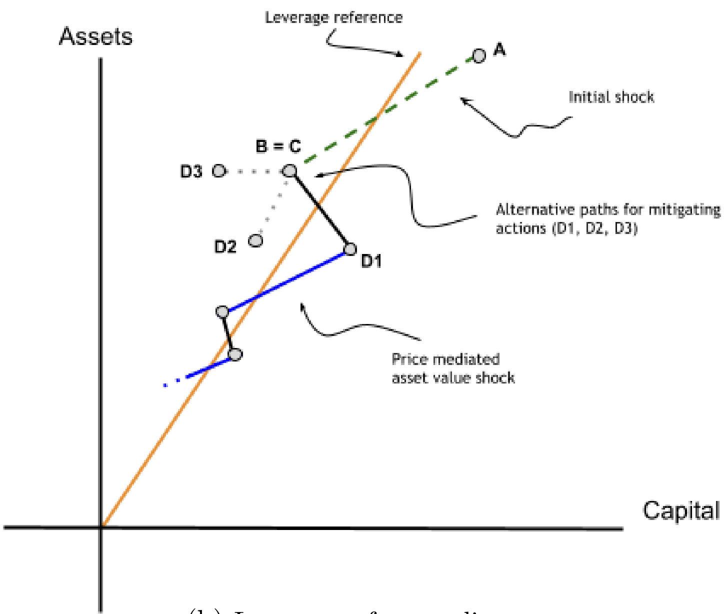
3.1 Assets and liquidity categories

Table 2 summarises the parameters defining the liquidity landscape. Our simulated classification distinguishes 12 asset categories based on the corresponding market depth (first row in Table 2). Next, each class of market depth is split into three subclasses defined by a unique combination of CB haircuts and repo haircuts[20]. A total of 36

[20] The values are chosen to scale in line with (ECB, 2020) and to give enough variability to test the model, while repo haircuts are in line with the data offered by the Acceptable Collateral haircuts



(a) Liquidity-solvency diagram.



(b) Leverage reference diagram.

Figure 2: Bank's liquidity-solvency and leverage-reference diagram. On top of the evolution of the timeline from the perspective of the capital and liquidity positions. Though represented as generic indicators, one can measure capital using equity and liquidity using cash and highly liquid collateral (or any other liquidity indicator). At the bottom, is the timeline from the perspective of the leverage ratio. Certain exogenous events or bank actions do not affect the position directly (B=C) or might affect it along diverse paths. For example, C-D1 is the typical path for asset sales aimed at restoring the leverage above a threshold level, C-D3 is the typical path of collateralized credit, and C-D2 is the result of a mixed mobilization.

liquidity classes gives an exact partition of the assets universe. Risk weights for the computation of the RWCR and haircuts of the LCR are defined for the 12 initial

of the LCH Clearnet group.

		Market depths (bn EUR)											
		A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12
		100	50	20	13	5	1	0.9	0.5	0.3	0	0	0
Haircuts	CB	0.01	0.03	0.03	0.03	0.04	1	0.05	0.1	1	0.2	0.25	0.4
	Repo	0.005	0.01	0.02	0.025	0.03	0.03	0.03	0.08	0.08	0.1	1	1
	CB	0.01	0.02	0.02	0.04	0.08	0.04	0.05	0.08	0.1	0.15	0.2	0.35
	Repo	0.01	0.02	0.02	0.04	0.08	0.04	0.04	0.08	0.1	1	1	1
	CB	0.02	0.04	0.02	0.04	0.06	0.06	0.1	1	0.15	0.2	0.1	0.3
	Repo	0.025	0.06	0.04	0.05	0.08	0.08	1	1	1	1	1	1
		Regulation parameters											
	Risk weights	0	0.1	0.1	0.2	0.35	0.5	0.7	1	1	1	1	1
	LCR hcs	0	0.1	0.15	0.15	0.2	0.2	0.8	0.8	1	1	1	1

Table 2: Asset categories identified by a unique combination of market depths, CB haircuts and Repo haircuts. Null market depths are assigned to non-marketable assets, while when the haircuts are equal to one, they are not accepted in that specific credit segment.

categories and are reported at the bottom of Table 2.

3.2 Model initialisation

The environment is populated by two macro groups of agents: $N_B = 50$ banks and $N_D = 50000$ depositors[21]. Banks belong to one of the four business models inspired by the clustered figures provided by Farnè and Vouldis (2021) for the Euro Area banking system, in the context of the supervisory reporting of the SSM, defining four subpopulations distinguished by the relative amount of the liabilities items. The general characteristics of each subpopulation are reported in Table 3 for the categories that are relevant to our application. The values set the reference points around which each subpopulation of banks distributes when the model is initialised[22]. Reference loan share populates the three categories A10-A12 uniformly in the table above. In comparison, the remaining percentage of assets is assigned to the 27 remaining categories following the typical distribution of the liquidity overlaps as in Cont and Schaanning (2017a)[23]. The size of banks is drawn from a lognormal distribution with mean and variance at the bottom of Table 3.

Each depositor deposits at a maximum of 5 banks. The distribution of deposits is Pareto-like so that the total amount of deposits matches the values for each bank[24]. Depositors can be of two types defined above, stable and informed, with stable depositors being 70% of the total depositors' population and uniformly distributed across banks.

[21] The ratio between depositors and banks numbers is only illustrative. Anyway, as anticipated above, one should think of the depositor representation as a way to parametrise the stochastic process modelling the run-off of credit-sensitive fundings.

[22] The distributions are Gaussians centred in the reference share with variance reported in parenthesis.

[23] See Fig. 8 therein and notice that the construction of the matrix of liquidity weighted overlaps is independent on the number of the assets categories.

[24] Distributions parameters are designed to guarantee an approximated match of the depositor-bank relation, minor corrections of banks and depositors sizes are implemented when the model is initialised to ensure consistency, but the distributions remain substantially unchanged.

	CC	SH	TC	WF
Deposits	35% (3%)	40% (3%)	25% (3%)	30% (3%)
Debt	50% (5%)	50% (5%)	60% (5%)	55% (5%)
Equity	15% (1%)	10% (1%)	15% (1%)	15% (1%)
Loans share	55% (5%)	75% (5%)	75% (5%)	60% (5%)
N banks	18	21	12	29
Size parameters	23 (0.7)	21 (0.4)	23.5 (0.7)	22 (0.6)

Table 3: Mean and variances (in parenthesis) for the relative quantities for the key items in the banks' balance sheets for each subpopulation. Reference values are borrowed from the cluster analysis of Farnè and Vouldis (2021). Number of banks for four different bank business models and parameters of the lognormal size distribution for each subpopulation. CC = Complex Commercial; SH = Security Holding, TC = Traditional Commercial, WF = Wholesale Funding

Parameter	Description (reference formula)	Value
N_B	Total number of banks	80
N_D	Total number of depositors	$5 \cdot 10^5$
ξ_i	RWCR limiting threshold (4)	$0.08\,\forall i$
δ^d	Depositors run-off sensitivity (4)	15
δ^{un}	Unsecured credit run-off sensitivity (5)	$+\infty$
δ^{rp}	Repo run-off sensitivity (5)	$+\infty$
ψ	Access to unsecured credit sensitivity (6)	15

Table 4: Parameters summary for the simulated scenario.

The remaining model's parameters are summarized in Table 4. Notice that for this first test of the framework, we restrict the sources of liquidity shocks to the run-off of informed depositors while modelling sticky the other funding sources.

3.3 Properties of the model

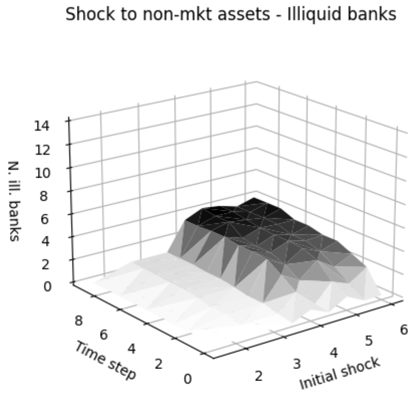
We simulate the timeline of the model for 10 iterations and given that the model is not fully deterministic due to the stochastic processes ruling the depositors' and banks' choices, we present the outcome as the average of 20 different runs.

Looking at banks' defaults, we infer from the representation in Figure 2a that after the initial shock, banks' paths have two main possible trajectories in the liquidity-solvency diagram: either they sell assets or they search for collateralized credit. The path followed is determined by the initial shock but depends on the unfolding dynamics of the environmental (systemic) variables after that. Systemic effects mark the difference with stress test models restricting the analysis to a single bank's balance sheet (see e.g. Cont et al., 2020) and generate complex interactions within agents in the financial system. Fig. 3 shows the number of defaults at each step for various shock intensities prompted to non-marketable assets (A10-A12 of Table 2). For our simulated system, we observe that insolvency is the most common mode of failure, while only a few units are illiquid. Failures due to illiquidity anticipate and foster the subsequent rounds of insolvency defaults induced by price-mediated contagion. Non-contemporaneity is determined because price shocks transfer to balance sheets at the end of each step and internalise at the beginning of the following step. In other words, if the shock is strong enough to induce liquidity defaults in a few banks, the recourse to fire sales of these banks and other shocked institutions triggers a price spiral that eventually affects bank solvency.

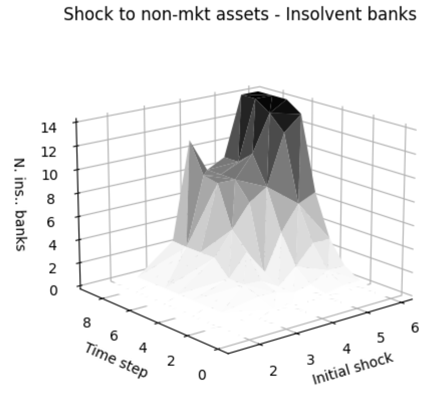
As in Cont and Schaanning (2017a), the mere fact that both failure modes are possible is not a distinctive feature of all stress tests. Duarte and Eisenbach (2021) and Greenwood et al. (2015) model all assets as readily available for deleveraging so that they can never be illiquid in practice. In general, deleveraging models only model illiquidity as the impossibility to restore their leverage ratio above a subjective threshold (including of Cont and Schaanning, 2017a), and not as a funding run-off that banks cannot counterbalance. Fig. 3 also shows the existence of a minimal level for a shock to have system effects and trigger a series of insolvency failures. For the analysed system, that is around a 4% shock to all the classes of non-marketable assets (columns A10-A12) in the configuration of Table 2. The existence of thresholds is confirmed by the output of Fig. 4 which shows a clear jump in the equity loss per banking type between 4% and 5%.

Regarding the evolution of bank fundamentals, our extension differs from models where the value of a single indicator is used as a reference for the mitigating actions (Cont and Schaanning, 2017a; Coen et al., 2019). In such models, the multiplicity of linkages between the dynamics of financial distress and the fundamental indicators of the banks is limited. In our setting, therefore, the solvency-liquidity interplay determined by the susceptibility of credit-sensitive fundings and the inclusion of the collateral framework among the mitigating actions originate a complex evolution of banks' regulatory ratios.

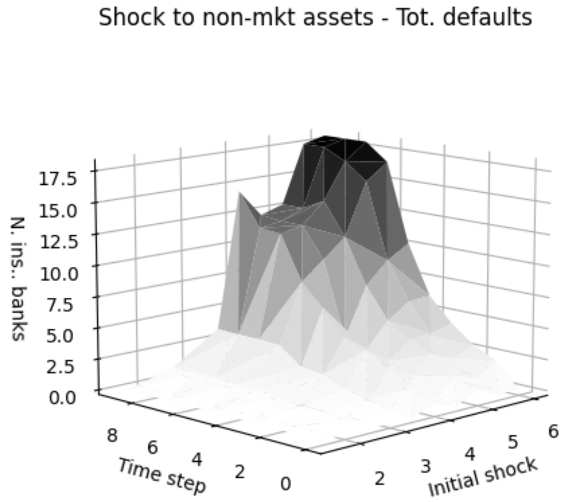
Notice that the intensive and extensive margin determines a shift in the regulatory ratio distributions. Namely, they can also change because the active (non-defaulted banks) population shrinks. Fig. 5 shows the evolution of the LCR and the RWCR distribution for the four bank types. We notice how the crisis unfolds at different paces according to banks' balance sheet composition. Focusing on a bank from group 4, we see that banks in that class have the instruments to sustain their capital ratio throughout the evolution of the crisis, drawing from their reserves of high-quality assets or cash and thus depleting their liquidity coverage ratio. However, the opposite dynamics are also possible. Banks in group 3, for example, have almost constant median LCR. At the same time, the RWCR, which had already deteriorated after the initial shocks, declined significantly and fell below the levels defined by the regulatory minima.



(a) Illiquid banks.



(b) Insolvent banks.



(c) Total number of defaults.

Figure 3: The number of defaults for different time steps and intensity of the initial shock.

3.4 Stress outcomes and the collateral framework

As an experimental setup, we analyse the sensitivity of the results to the Central Bank haircut values by modelling the policy's responses to the Covid-19 crisis that occurred between March and April 2020 in the Euro Area. At that time, the Governing Council of the ECB "decided to temporarily increase its risk tolerance level in credit operations through a general reduction of collateral valuation haircuts by a fixed factor of 20%"[25]. We prompt, therefore, a 5% shock and 6% in non-marketable assets values, to which the Central Bank responds by reducing the haircuts, modulating the intensity of the easing from -5% to -25%. We analyse stress tests of the ten-time steps each, and the outcomes presented are again the simple average of 20 runs.

[25] https://www.ecb.europa.eu/press/pr/date/2020/html/ecb.pr200407~2472a8ccda.en.html.

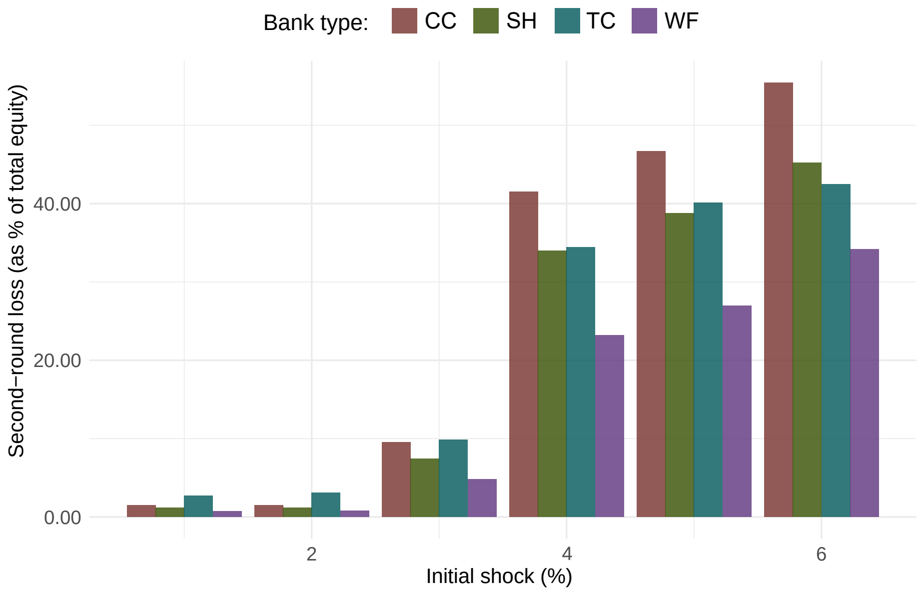


Figure 4: Bank equity losses for different business models and different initial shocks. Note: CC = Complex Commercial; SH = Security Holding, TC = Traditional Commercial, WF = Wholesale Funding.

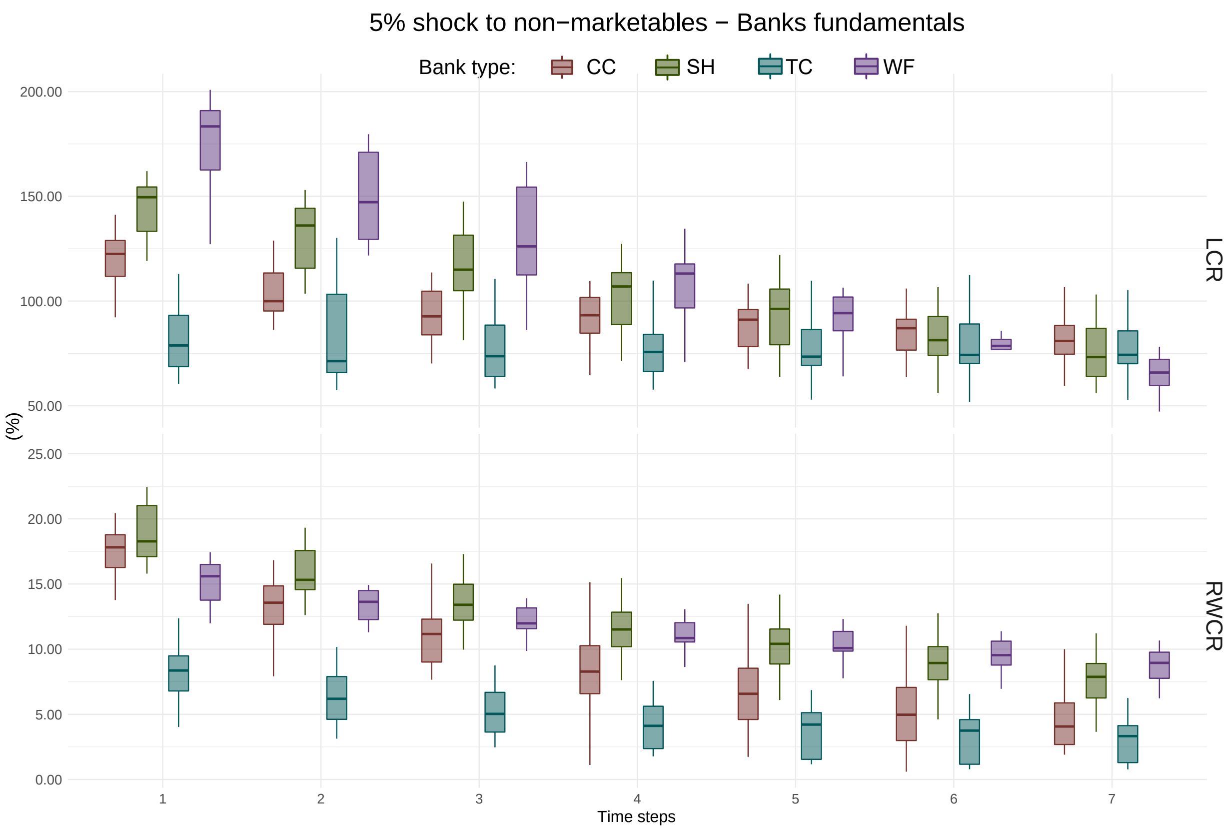


Figure 5: Distribution of the liquidity coverage ratio (LCR) and risk-weighted capital ratio (RWCR) per bank business model. The sequence shows the evolution in the first seven steps after an initial shock of the 5% for non-marketable assets. Note: CC = Complex Commercial; SH = Security Holding, TC = Traditional Commercial, WF = Wholesale Funding.

Looking at defaults (Fig. 6), we notice that there is a threshold after which the expansion of the collateral framework affects financial stability. The threshold varies with the shock level and tends to reduce around 15% of the haircuts in our proposed setting. Secondly, we observe that the broadening of the collateral framework almost exclusively affects the insolvency defaults. As anticipated in section B, such a finding can be explained by the fact that the collateral framework broadening not only changes the condition under which banks access liquidity at the Central Bank but also limits the banks' recourse to other funding channels eventually dampening the market turmoil. Fig. 7, 8 and 9 show the differential effect of collateral broadening on equity loss and other fundamentals. Looking at the capital loss, the impact of a change to the collateral framework seems homogeneous across different bank types, with banks in group 2 benefiting more from the intervention than the other types.

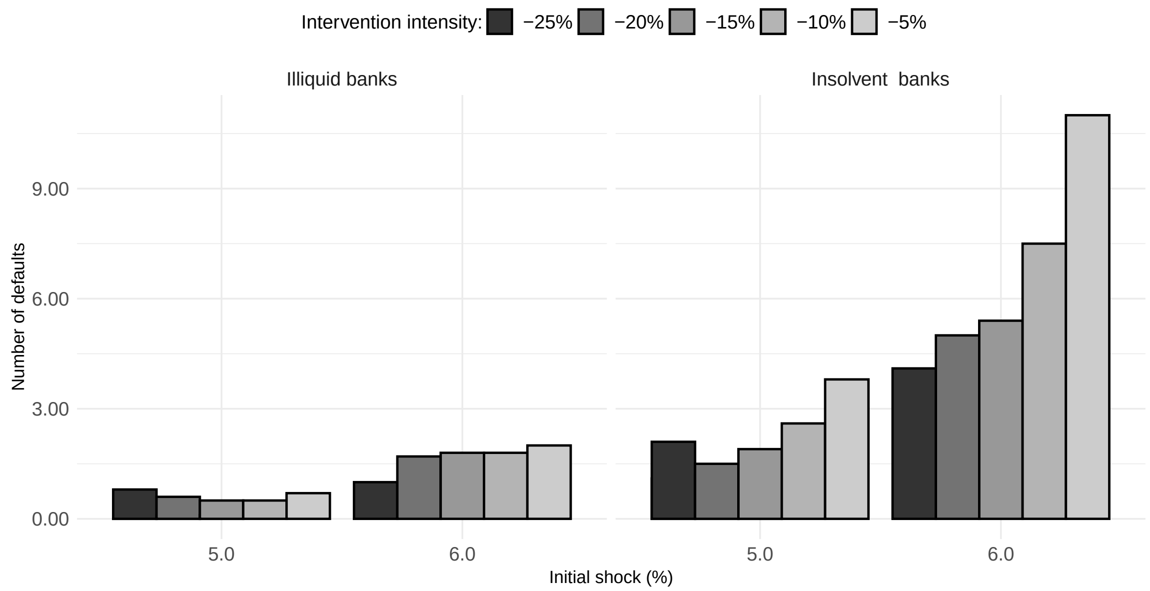


Figure 6: Illiquid and insolvent banks for 5% and 6% shocks to non-marketable assets for different values of collateral framework expansion

4 Data for the Euro Area

The model as it is designed is particularly demanding in terms of the granularity of the data sources. Recent developments in bank-level data reporting and harmonisation allow recovering an empirical decomposition of the balance sheets of the Eurosystem banks based on the integration of the Financial Information Reporting (FINREP) and the Analytical Credit Datasets (AnaCredit) of the European System of Central Banks. Such a decomposition of the balance sheets can be integrated with the key characteristics of the collateral framework and information on asset liquidity.

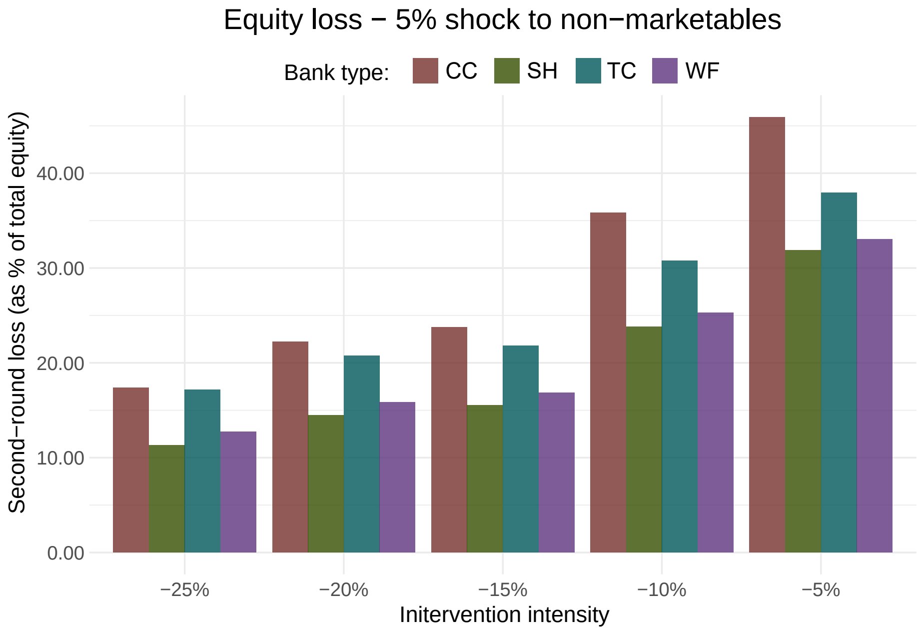


Figure 7: Bank equity losses after ten steps given an initial shock of 5% to non-marketable assets for different bank types and under the different interventions of the Central Bank. Note: CC = Complex Commercial; SH = Security Holding, TC = Traditional Commercial, WF = Wholesale Funding.

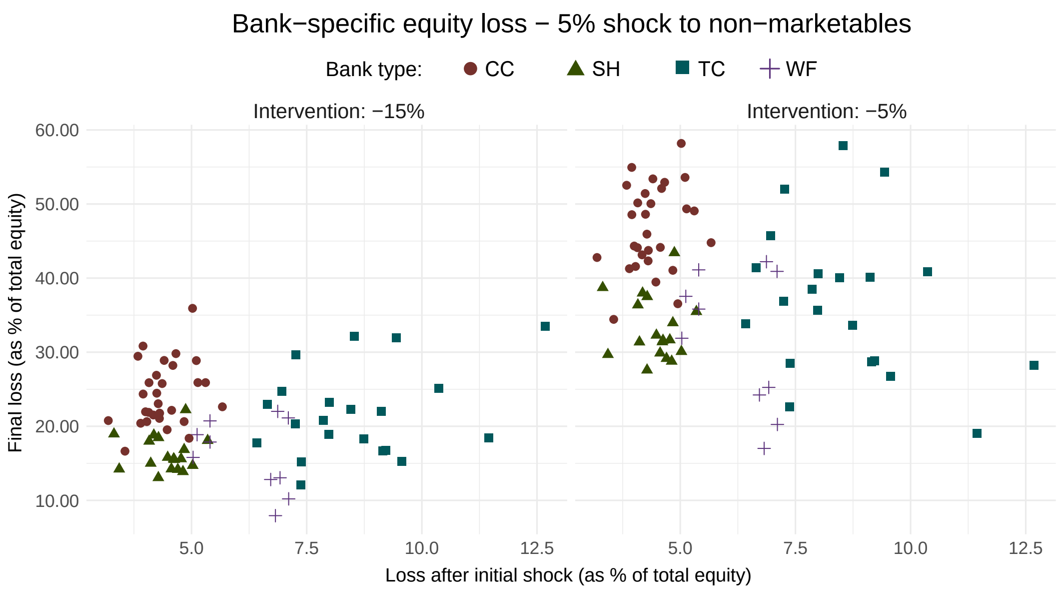


Figure 8: Bank-specific equity losses after ten simulation steps vs the initial loss after the exogenous shock (as a percentage of bank equity). Results for two levels of intervention. Note: CC = Complex Commercial; SH = Security Holding, TC = Traditional Commercial, WF = Wholesale Funding.

We apply the model to 67 significant institutions in the Euro Area.[26] The section briefly describes the data and defines our structure of asset classes.

[26] Significant institutions are identified by criteria of size and economic relevance. For a description of the criteria, see `https://www.bankingsupervision.europa.eu/banking/list/criteria/html/index.en.html`.

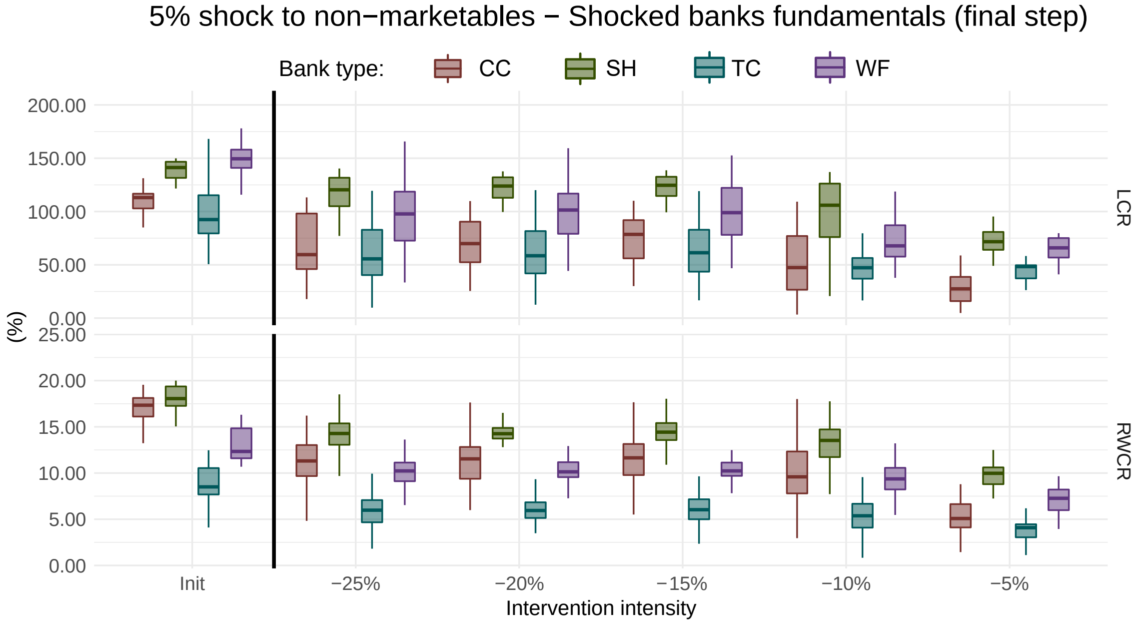


Figure 9: Distributions of the liquidity coverage ratio (LCR) and risk-weighted capital ratio (RWCR) per bank type. Snapshot of the values at the tenth simulation step of the stress test under different Central Bank intervention intensities compared with the initial distributions (left side). Note: CC = Complex Commercial; SH = Security Holding, TC = Traditional Commercial, WF = Wholesale Funding.

4.1 Granular representation of banks' balance sheet

We build the banks' balance sheets using the Financial Reporting Framework (FINREP) and AnaCredit, the instrument-level dataset of the ECB, as of December 2021.

We divide assets into tradable and non-tradable assets [27]. Both asset types are then additionally distinguished between encumbered and unencumbered assets.[28] While all assets are differentiated by country, loans to non-financial corporations are then disaggregated across the following dimensions: i) country, ii) type of counterpart, iii) type of securitisation, iv) industrial sector (NACE 2), v) class of risk, and vi) maturity.[29]

A novelty of the paper is the joint use of Finrep and AnaCredit as data sources. In addition to Finrep, AnaCredit enriches balance sheet data with information on

[27] See Tables C.2 and C.3.

[28] see Tables C.4 and C.5 and Appendix D.

[29] We consider countries in Euro Area and include Denmark, Norway, Sweden, Great Britain, Switzerland, Australia, New Zealand, USA, Canada, China, Hong Kong, Japan, South Korea, and Singapore (the main OECD economies). All other countries are aggregated in a single foreign economy. See Table C.6 for the composition of balance sheets across the country of counterpart and Table C.7 for the detail of the country composition for non-financial loans based on AnaCredit. Types of counterparts include central banks, government, non-financial institutions, and other financial institutions. The type of securitisation distinguishes between traditional securitisation, synthetic securitisation, and not securitised. We construct three risk classes using the probability of default reported in AnaCredit, i.e. lower than 0.1, between 0.1 and 0.4, and above 0.4 (see Table C.8). The probability of default is reported at the loan level. If the loan level value is missing, we then consider the average probability of default in the industrial sector. Classes of maturity distinguish assets into three classes: below 3 years, between 3 and 7 years, and above 7 years (see Table C.9.

the encumbrance, the type of securitisation, the industrial sector, the risk, and the maturity of each bank instrument. Since the scope of the two datasets can differ[30], we disaggregate the aggregate value of non-financial institutions' assets reported in Finrep by the relative weights computed using AnaCredit. Such an approach ensures that the aggregate sum of assets remains unchanged, while it allows disaggregating assets by type of securitisation, industrial sector, class of risk, and classes of maturity. We are, therefore, able to include more than 500 asset classes.

4.2 Asset liquidity

As for the simulated model, the asset classes are characterised by a triple of parameters: market depth, Central Bank haircut and repo haircut. This approach shares the perspective of heterogeneous liquidity models as Cont and Schaanning (2017a) and Coen et al. (2019), in contrast to Greenwood et al. (2015) which assume a uniform market depth of 10^9 (EUR bn).

For the market depths, we apply a linear impact model for the marketable asset μ:

$$D_\mu = c\,\frac{\mathrm{ADV}_\mu}{\sigma_\mu}\sqrt{\tau}$$

where ADV is the average daily trading volume (in EUR), σ_μ the daily volatility (in % points) associated with the asset class and τ is the liquidation horizon, and c is a coefficient set equal to 0.3 as in Cont and Schaanning (2017a)[31]. As for the parameters, τ is set to be equal to 10 for a liquidation horizon of two weeks and $c = 0.3$ as in Cont and Schaanning (2017a). On the chosen impact function, just notice that while finer liquidity measures are available and can be more reliable and precise, this one allows us to get estimates from publicly available data and to get a consistent integration with the balance sheets decomposition outlined above.

Volatilities are obtained from the daily S&P returns for the specific asset categories and countries[32,33,34]. We get the estimates of the ADV for government bonds from public authorities, governments and central banks online sources (see Coen et al., 2019, for a detailed list of references for both volatilities and volumes). Data on daily volumes for corporate bonds and equity instruments are available only for the US at SIFMA[35],

[30] AnaCredit contains records only for consolidated positions above 25.000 euros and only for legal entities (e.g. households are not included)

[31] The coefficients generate from square root model for market depth, and its derivation is beyond the scope of this paper. We refer to Cont and Schaanning (2017a) for a thorough discussion on the adequacy of this price impact measure and its calibration.

[32] Government bond indices `https://www.spglobal.com/spdji/en/index-family/fixed-income/treasury-sovereign-quasi-government/sovereign/#overview`.

[33] Equity indices: `https://www.spglobal.com/spdji/en/index-family/equity/`.

[34] Corporate bonds indices: `https://www.spglobal.com/spdji/en/index-family/fixed-income/corporates/#indices`.

[35] `https://www.sifma.org/resources/archive/research/statistics/`.

we integrate the figures for the other countries using BIS outstanding amounts[36] and assuming proportionality of the turnover ratio. For example, taking government and equity volumes and exceptional amounts for the US, a parameter κ is estimated as[37]:

$$\frac{\text{ADV}_e^{US}}{\text{OA}_e^{US}} = \kappa \frac{\text{ADV}_g^{US}}{\text{OA}_g^{US}}$$

and then for a generic country (C):

$$\text{ADV}_e^{C} = \kappa \frac{\text{ADV}_g^{C}}{\text{OA}_g^{C}} \text{OA}_e^{C}$$

When data are not available at the mentioned references, we set the associated market depth as null and assume that the particular exposure is non-marketable.

Central Bank haircut estimates for the asset categories are obtained from the Eligible Assets dataset (Sept 2021)[38]. Simple averages are taken for each unique asset type, debtor group and country. For non-marketable assets, the categorization imposed through the AnaCredit variables allows settling the haircuts in agreement with the ECB official guidelines ECB (2020).

For repo haircuts, we get a proxy for the primary government instruments from the accepted collateral haircuts of LCH Clearnet.[39]

4.3 Stress scenarios

We define stress scenarios as exogenous shocks to selected asset classes given the above representation. A vector of percentage loss defines shocks (see Eq. (1)) and is imparted to the balance sheets at the beginning of the timeline defined in section 2.4. We define three scenarios:

1. **EBA 2021:** we use the losses implied by the 2021 EU-wide stress test of the European Banking Authority as a benchmark. That exercise provides information on the envisaged losses under two scenarios for 50 European banks within three years (2021-2023). We calibrate a diffused shock to non-marketable assets to match exactly the bank-specific shift in the leverage ratio under the *adverse scenario*[40]. In practical terms we take as input ΔLR_i for bank i from EBA (2021b) and set

[36] `https://stats.bis.org/statx/srs/table/c1`.
[37] In complete analogy, the turnover ratio is also used for corporate bonds and other instruments.
[38] `https://www.ecb.europa.eu/paym/coll/assets/html/list-MID.en.html`
[39] See `https://www.lch.com/collateral-management/ltd-collateral-management/ltd-acceptable-collateral/ltd-acceptable-securities`
[40] For all the relevant information on the definition of the two scenarios, the bank included and the general methodology see EBA (2021a).

$$\epsilon_1^M = \ldots = \epsilon_{K_M}^M = 0 \qquad \epsilon_1^M = \cdots = \epsilon_{K_N}^N = \alpha_i \qquad \text{s.t.}$$
$$\Delta(\text{LR}_i) = 1 - \frac{\text{LR}_i}{\underline{\text{LR}}_i(\alpha)} \tag{16}$$
$$\underline{\text{LR}}_i(\alpha) = \frac{e_i - \alpha \sum_\nu^{K_N} A_{\nu,i}^N}{c_i + o_i + \sum_\mu^{K_M} A_{\mu,i}^M + (1-\alpha) \sum_\nu^{K_N} A_{\nu,i}^N}$$

The bank-specific leverage ratio loss is specified for 33 banks that are the intersection between the EBA dataset and ours. The institutions not included in the EBA datasets are shocked using the country means or the overall mean if the country is absent. Notice that it is an asymmetric shock, and its calibration through the EBA exercise is fundamental to understanding the differential impact on European banks. However, when implementing the test, we regulate the intensity of the shock, rescaling uniformly the coefficients α_i. The scaling factors define five intensity profiles. I1: 0.05, I2: 0.1, I3: 0.15, I4: 0.2, I5: 0.25.

2. **Russian shock:** Losses materialize with different intensities on sovereign exposures and commercial and retail exposures of Russia and nearby countries with five different intensities profiles according to Table 5.

Country	Assets	Assets value shock				
		I1	I2	I3	I4	I5
RU	Government and regional debt	0.5	0.6	0.75	0.8	0.8
RU	Loans to non-financial corporations	0.5	0.6	0.75	0.8	0.8
RU	Loans to households	0.5	0.6	0.75	0.8	0.8
EE, LT, LV, SK SI	Government and regional debt	0.01	0.05	0.1	0.15	0.2
EE, LT, LV, SK SI	Loans to non-financial corporations	0.01	0.05	0.1	0.15	0.2

Table 5: Shocked assets and intensity profile for the Russian scenario.

3. **Southern European shock:** Losses materialize with different intensities to non-financial corporations and households of southern European with five different intensities profiles according to Table 6.

Country	Assets	Assets value shock				
		I1	I2	I3	I4	I5
IT, PT, ES, CY, GR, MT	Loans to non-financial corporations	0.01	0.05	0.1	0.15	0.2
IT, PT, ES, CY, GR, MT	Loans to households	0.01	0.05	0.1	0.15	0.2

Table 6: Shocked assets and intensity profile for Southern European countries scenario.

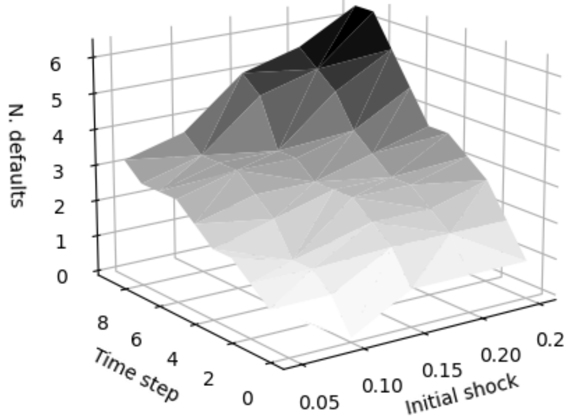
5 Results

The severity of each scenario depends on different balance sheets composition and, in particular, on the exposure in the regions and segments subject to the initial shock. Table 7, provides the average initial loss (in % of equity) for selected intensities. We

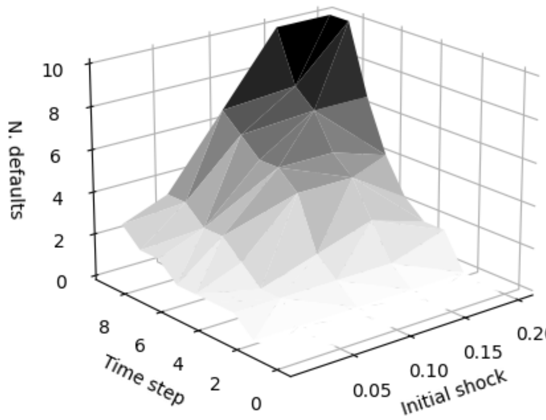
		Scenario EBA			Scenario East. cnt			Scenario South. res.		
		I1	I3	I5	I1	I3	I5	I1	I3	I5
Average equity loss (%)	Init. loss	1.27	3.30	5.32	1.11	1.58	2.09	1.58	14.32	25.47
	Tot. loss	8.99	11.04	13.59	8.43	9.38	9.78	9.64	24.10	34.21

Table 7: Average percentage losses of the stress scenarios. The initial losses are those induced by the exogenous shock, while total losses materialize at the end of the stress test.

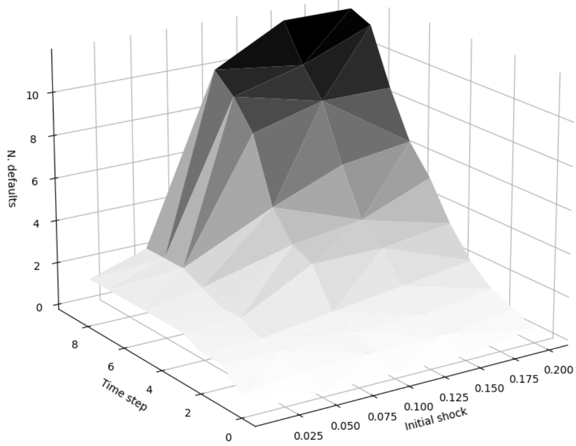
notice that even minimal initial shocks at the initial step are sufficient to trigger substantial losses in the aggregate at the end of the ten steps. For the applied shock intensities, we do not find evidence of the existence of a tipping point in the shock intensity line as in Cont and Schaanning (2017a). The endogenous dynamics unfolding after the initial shock determine a smoother transition from a status of financial stability to the materialization of the systemic losses implied by the indirect contagion. This appears from the surface plots for the Eastern country scenario (Fig. 10b) and the Southern residential scenario (10c).



(a) Defaults for EBA scenario.



(b) Defaults for Eastern European scenario.



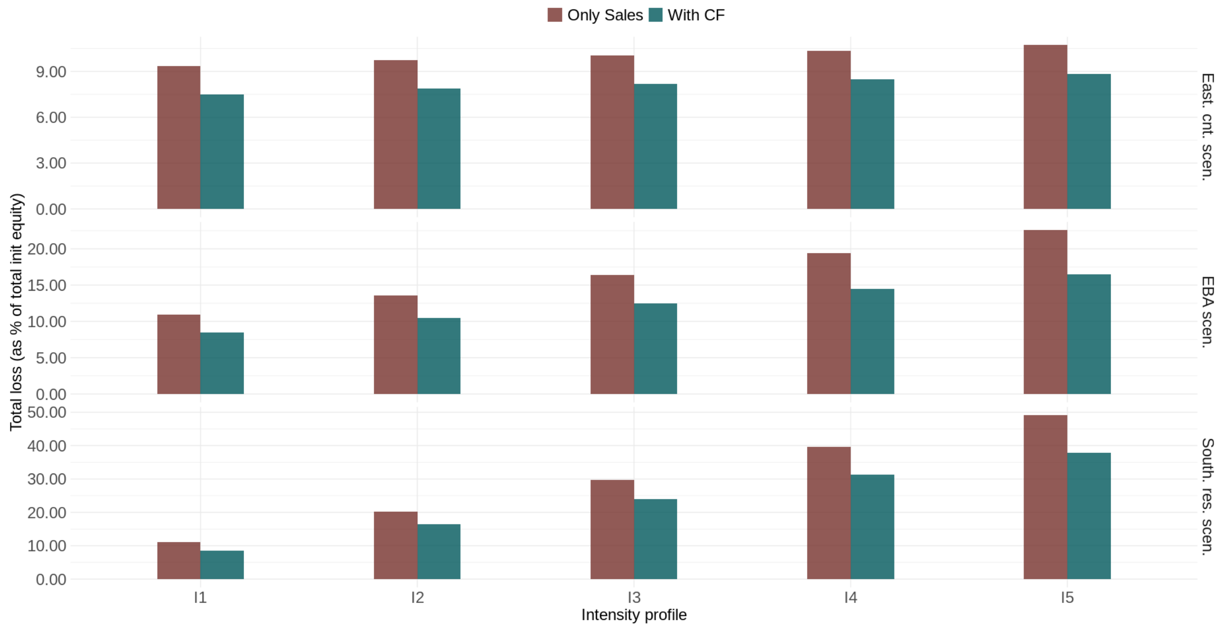
(c) Defaults for Southern scenario.

Figure 10: Number of defaults for different time steps and intensity of the initial shock

Fig. 10a reports the results for the EBA scenario. While it is characterized by asymmetric the intensity of the shocks, in the sense that they affect different banks with different intensities, the EBA scenario is homogeneous to the asset classes as the initial value shock is deployed to all non-marketable assets of all banks, irrespectively of their exposures towards particular markets or segments. In this light, we can interpret the constant level failures, independent from the shock value and occur after a few iterations, as defaults induced directly by the initial shock on banks that enter the stress test with already deteriorated fundamentals. This evidence suggests that the experiment should be extended to higher levels of intensity shocks to generate significant aggregate dynamics.

To strengthen our results, we provide a quantitative analysis of the collateral framework's role in supporting the European financial system during periods of stress. The analysis compares the relevant indicators where banks can use assets as collateral in lending transactions versus cases where they raise liquidity only by selling them. Results indicate that, on average, stress testing with the collateral framework leads to the preservation of 5% equity losses across all three scenarios and all the intensity profiles, with system losses increasing from 18.19% to 23.06% (Fig. 11). The effect is also evident when considering the lower end of the distribution. It is more pronounced as the intensity and severity of the scenario increase, with equity losses in the 'Only Sales' model exceeding the collateral framework model by 16 points. Fig. 11 shows differences between the scenarios as the intensity profiles change, with the effect of the collateral framework being constant in the case of shocks to assets linked to Eastern countries and increasing as the intensity rises for the other two scenarios, particularly for the southern country residential scenario. This suggests that for shocks involving more banks and a broader class of assets, as those of EBA and southern residential scenarios, the collateral framework induces a reduction in asset sales, thus supporting prices and slowing down the contagion mechanism at each round. This explains why the gains in terms of equity losses increase more than linearly.

Fig. 12 shows the evolution of the distributions of fundamentals for the entire financial system. The two versions of the model for the three scenarios are compared under the intensity profile I3. The results show that the collateral framework supports banks' fundamentals, particularly at the first step after the exogenous shock. Over time, the median values for the two models get closer, primarily due to the differential impact of the selection effect. With 5-10% more defaults mainly occurring in the second part of the time span, in the 'Only Sales' specification, most banks with deteriorated fundamentals are selected out and do not participate in the aggregate statistics. Two other points are worth noting. First, the collateral framework contributes significantly to supporting all fundamentals, with a significant difference for the three distributional quantiles considered, albeit with some differences. Second,



Model	Min Loss (%)	Average Loss (%)	Q90 Loss (%)	Q99 Loss (%)	Max Loss (%)
With CF	6.70	18.19	39.00	63.55	66.52
Only Sales	8.99	23.06	48.48	79.67	83.85

Figure 11: Comparison between a simulation with the collateral framework and asset sales only. System-wide average bank equity loss as a percentage of initial bank equity for different scenarios and intensity profiles. Entries in the table display the minimum, maximum and average total losses in percentage points across different scenarios and intensity profiles.

the model provides evidence that banks with strong fundamentals (those in the 90th percentile) interact strategically with the collateral framework. As a consequence, an increase in the value of the 90th percentile of the main fundamentals in the first steps after the shock is to be interpreted as an overreaction of the banks willing to improve their condition, restoring the level of the indicators above a subjective threshold well above the regulatory requirements. This is what happens, for example, for the capital ratio (RWCR) in the EBA and southern residential scenarios.

Making the most use of our granular dimensions, we show that shocks affect countries asymmetrically (Fig. 13) and asymmetric is the impact of a collateral framework modulation or removal (Fig. 14)[41]. Previous observations on the EBA scenario are confirmed by looking at the distributions of the regulatory ratios (Fig. 13a). The dynamics for most countries are restricted to the initial shock and the immediate aftermath, showing evidence of a general spreading of the variances of the distributions, which stabilize from the third step onward. We observe interesting dynamics for a small country with few banks (last on the right). The subsequent shocks to assets value and loss of funding continue to bite, causing a general depletion of asset values

[41] The scope of Fig. 13 and Fig. 14 in the present working paper is to highlight the differential evolution and effects for different jurisdictions and not to illustrate country-specific stress levels. Hence the panels refer to non-overlapping pools of anonymized countries. Country-specific results are going to be developed more in detail in future works.

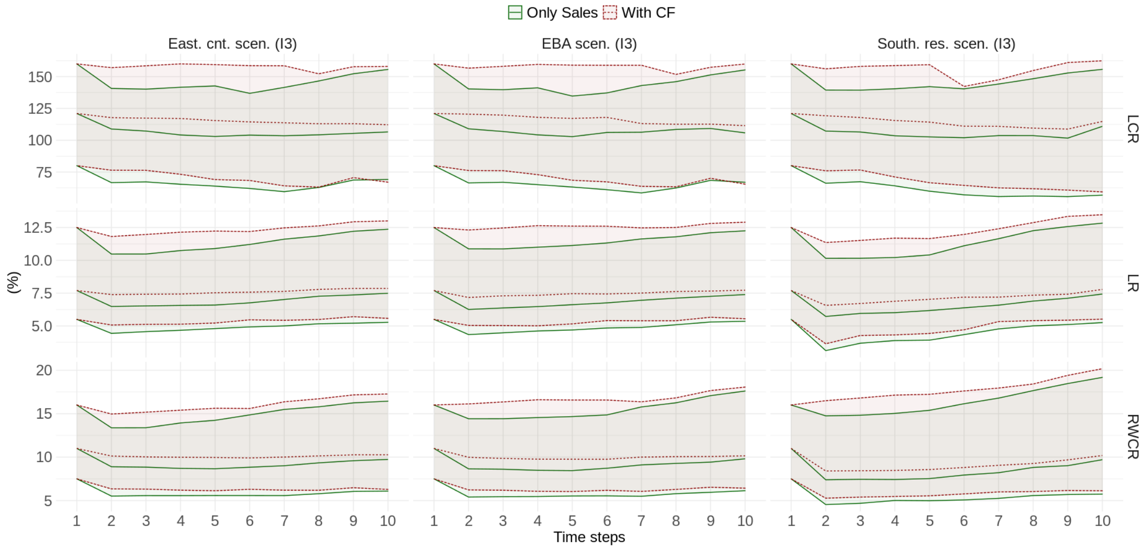


Figure 12: Time evolution of the distribution of the banks' fundamentals (median, 10th, and 90th percentile) comparing simulations with the collateral framework and asset sales only. Intensity profile = I3 (Tables 5-6)

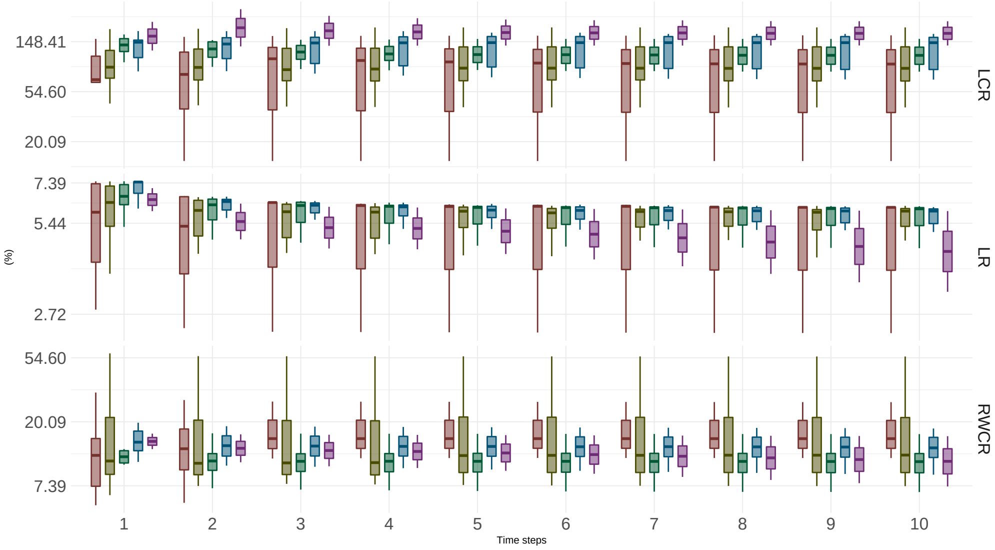
transferred directly to the leverage ratio. The same holds for the Russian shock scenario (Fig. 13b) where the distributional shifts after the first step are almost entirely restricted to the leverage ratios distribution of a single country.

For what concerns the Southern European shock scenario (Fig. 13c), the intensity of the initial shock generates sustained endogenous dynamics that are probably restricted to countries that are most exposed to the domestic residential market. In particular, for a country (the last on the right), the initial shock causes significant losses transferred directly to the capital and leverage ratio. The subsequent recovery is explained by failing banks leaving the population of active institutions, while second-round adjustments are due to the interaction with the liquidity environment.

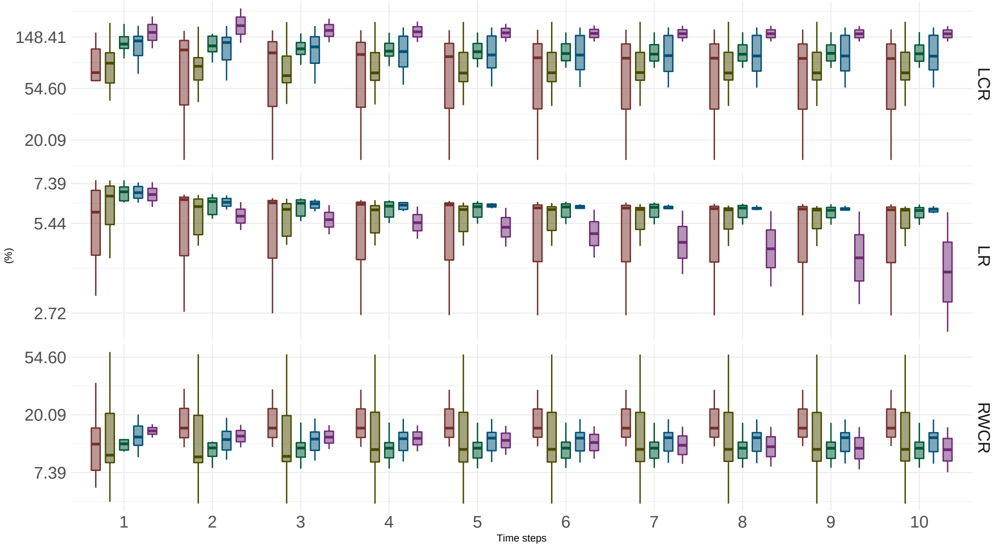
Finally, Fig. 14 zooms into country-specific distributions of the fundamentals, where the selection effect has been controlled for including in the analysed sample only the banks surviving until the end of the stress test. This outcome helps highlight how, while the general mitigating impact is confirmed, the effects of the collateral framework can be heterogeneous across jurisdictions depending on the scenario considered, with some cases showing zero or reversed signs. These differences being more and more significant as we disaggregate to the bank level.

6 Concluding remarks

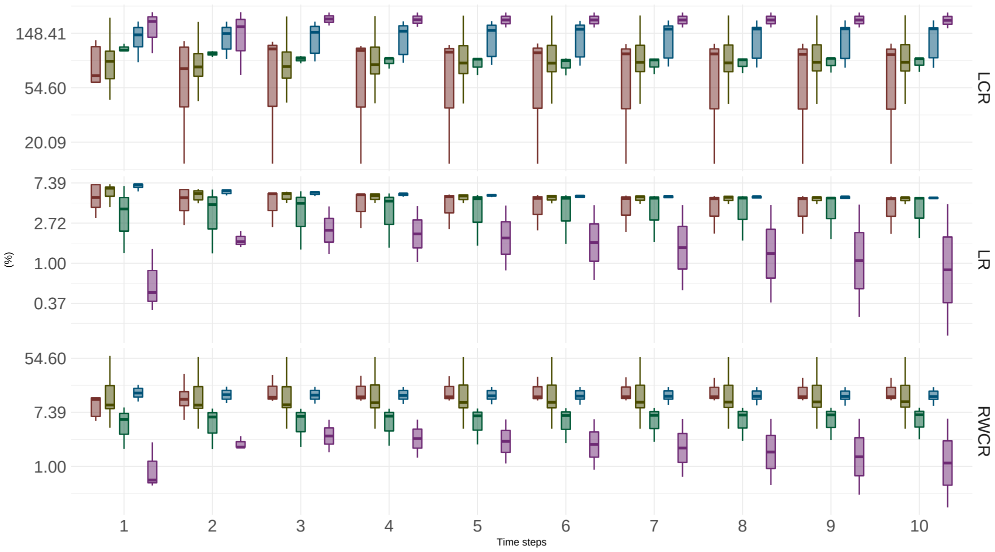
This paper develops a stress test model for a system of heterogeneous banks where multi-faceted liquidity shapes the outcomes of stress test outcomes. The proposed setting relies on a granular representation of banks' balance sheets which need to



(a) EBA scenario (I5).



(b) Eastern countries scenario (I5).



(c) Southern residential scenario (I5).

Figure 13: Distributions of the liquidity coverage ratio (LCR), the leverage ratio (LR) and the risk-weighted capital ratio (RWCR) for five selected countries (anonymized). Evolution at different simulation steps

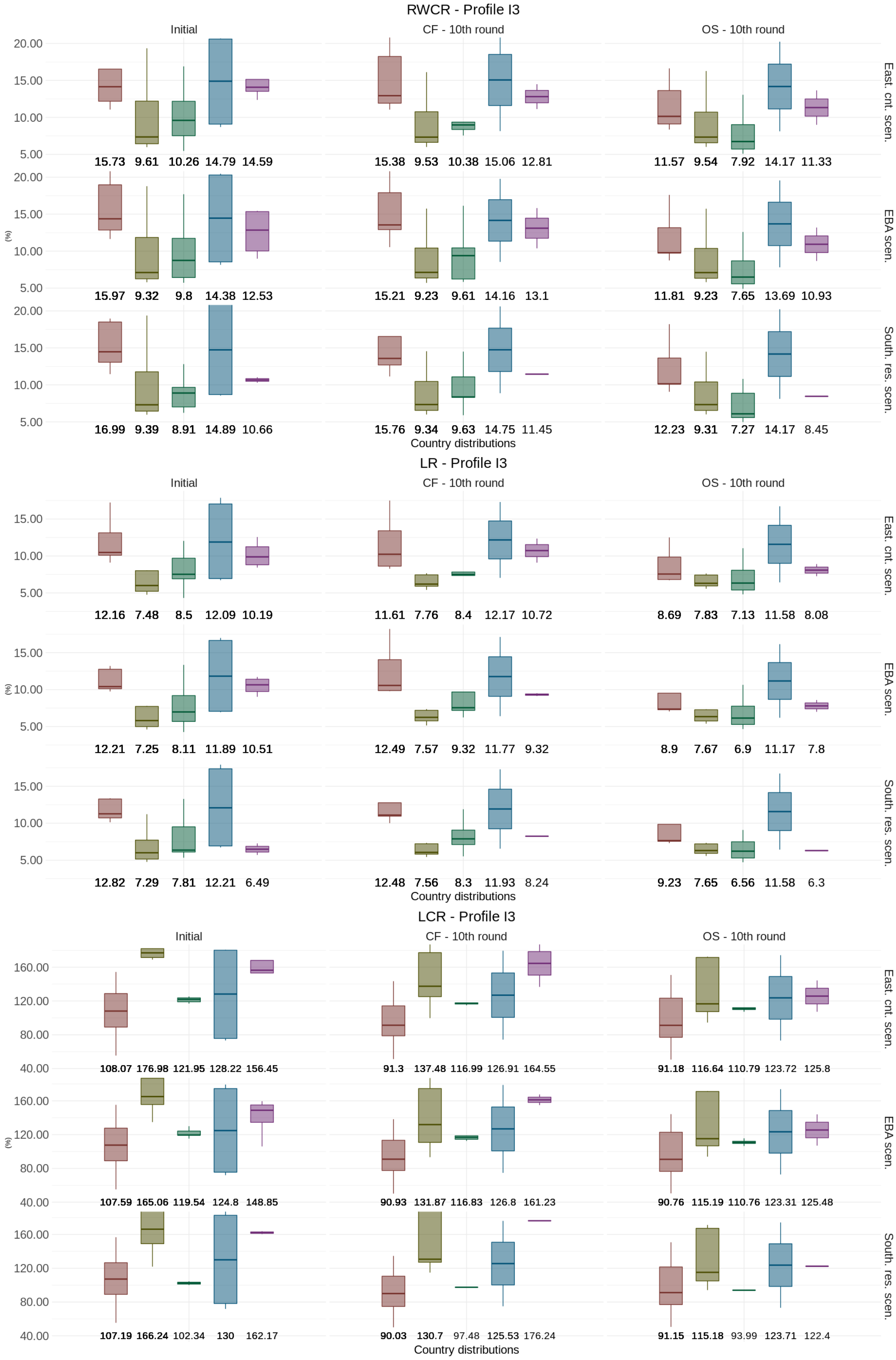


Figure 14: Distributions of banks fundamentals for five selected countries (anonymized). The columns display i) the distributions after the initial shock, ii) the end-of-simulation distributions for the model with the collateral framework (CF), and iii) the Only-Sales model (OS). Country averages are reported beneath the box plots. For all the columns, the sample is restricted to banks non-defaulting until the end of the simulation

distinguish asset classes along three liquidity dimensions defined by the characteristics and the terms of the exchange between the asset and readily available cash. The marketable assets can be sold at a market price that depends on a given market depth or used as collateral in a transaction in the private repo market or with the Central Bank at the conditions established in the Central Bank collateral framework. This framework outlines an operational framework where liquidity and solvency positions of banks non-linear interact in the unfolding of a financial crisis generated by exogenous shocks. The asset price movements determine systemic effects and thus depend on the intertwining of the network of common exposures and the haircuts and eligibility requirements for collateral. The stress test model relies on a granular representation of the balance sheet and allows to condition and measure of the banks' performances using regulatory ratios as representations of banks' fundamentals.

The model finds that systemic losses are reduced up to 17% in the most severe scenarios and on average around 5% when the collateral framework channel is available to banks. We emphasise, therefore, the importance of the Central Bank collateral framework as an instrument for financial stability.

We show how modelling a granular collateral framework significantly modifies the strategy space of banks facing a liquidity shortfall and eventually transforms the liquidity landscape by mitigating the turmoil in asset prices. Testing the model on a simulated financial system highlights the relevance of heterogeneity in the assessment of the impact of the collateral framework. If models were overlooking the heterogeneity of the balance sheet composition and banks' liquidity positions, they would undermine two relevant policy targets, i.e. asset market stability and fostering credit supply. On the former aspect, especially, we show how heterogeneous banks have likely divergent liquidity stress strategies and, consequently, their impact on asset market prices in a crisis might vary consistently. The effectiveness of central bank policies would be, therefore, enhanced by factoring in the asymmetric effects of haircuts when calibrating the collateral framework parameters to stabilise asset markets.

As for the outlook, with a theoretical simulation of the model, we highlight how the model's main properties can be used to address policy-relevant conclusions in future applications. The model can be used, for instance, to confirm the Bagehot "inertia principle": i.e. avoiding an expansion of the collateral framework, even though it might seem to prevent excessive reliance on Central Bank resources in the short run, could eventually lead to the opposite result. A milder reaction could in principle destabilise a larger share of banks that suffer from impaired access to market funding. Recourse to Central Bank credit, therefore, would be wider and prolonged to phase the financial system out of a crisis.

In the paper, we show how in stress test models where banks under stress could face a crisis via various mitigating actions, banks' strategies are relevant in the definition of the outcomes. To better capture the systemic effects of banks' activity, therefore, an empirical analysis of the patterns of collateral mobilization in the private repo market (Schaffner et al., 2019) or to the Central Bank (on the line of Jasova et al., 2021) is a natural complement for the model.

Nonetheless, the current study is constrained by some of its assumptions, which leave room for future extensions. To begin, we simulate constant haircuts for assets and the repo market, whereas haircuts may change during a crisis. Similarly, we use a linear function for asset pricing here, whereas non-linear functions could be tested to better fit price reactions during times of distress. Following that, an expanded modelling of depositor expectations could broaden the bank-run mechanism: we present here a trigger mechanism that can be fine-tuned using alternative behavioural mechanisms. Finally, we do model online indirect bank contagion via common exposures, so the paper does not examine direct contagion coming from possible second-round effects due to bank defaults. We leave potential extensions to future research.

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Appendix A. The collateral framework as a policy tool: a historical overview

Collateral frameworks of central banks (and their predecessors) have been frequently used for policy purposes, i.e. have been specified not only to serve risk protection but also to reach specific further public policy objectives. We will list in this section ten examples across the history of central banks and finally assign those in six classes according to the pursued policy goals, whereby sometimes measures supported more than one such goal:

i) Monetary policy: if collateral policies aim to achieve a monetary policy objective, such as price stability. The collateral framework can become decisive for monetary policy if conventional monetary policy is constrained by zero lower bounds. In this case, collateral policies can support banks in maintaining bank intermediation spreads moderate and therefore contribute to low refinancing costs of the economy for a given level of policy rates.

ii) Ex-ante liquidity policy: if the collateral framework aims at supporting the liquidity of financial markets and the ability of intermediaries to deliver liquidity transformation, such as to also moderate term and liquidity spreads and make favourable financing conditions for longer-term investments.

iii) Restoring ex-post financial stability: if the collateral framework aims at restoring financial stability after the outbreak of a liquidity crisis.

iv) Structural/industrial policy: if collateral policies aim at supporting real growth, either in general or via a specific industry, that is considered crucial.

v) Addressing market failures: if collateral policies aim at correcting an identified market failure that, e.g. distorts relative financial market prices.

vi) Social policy: if collateral policies aim at supporting low or very low-income households.

The model proposed in this paper does not cover all the objectives and rather focuses on financial stability. We nevertheless mention in this section all the policy goals to provide a comprehensive picture of the role of the collateral frameworks of central banks.

The initial motivation of any collateral requirement is to protect the lending Central Bank from financial losses in case of a default of the borrower. Therefore, this perspective is also the first basis for establishing which assets are eligible, valuing collateral carefully, and imposing haircuts. It is universal because any commercial entity without policy objectives will determine its collateral framework based on such considerations.

Consider now the ten examples throughout history.

(1) A public lending facility to save the poor from usury: the Italian Monti di Pietà as of 1463 and the Hamburger Bank in 1619. Monti di Pietà were one early predecessor of central banks. Their lending facilities were integrated via the Naples public banking system (starting in the 1580s), the Hamburger Bank (1619) and the Stockholm Banco (1658)/Riksens Ständers Banco (1668) into central banking. However, their initial motivation was social: to prevent poor citizens from taking recourse to private "usurers" who would eventually harm the debtors more than help them (Muzzarelli, 1999; Barile, 2012; Carboni, 2012). The Hamburger Bank took up this social aspiration of the Monti di Pietà in 1619, of which the preamble of the statutes of its lending-arm states (Bindseil, 2019, p. 25):

> According to experience, which also has been reported bitterly to the City Council, people who need to borrow substantial amounts of money in an emergency or for their business have to pay excessive interest rates and pledge collateral, to egoistic, advantage-seeking individuals, in contradiction with Christian love. Therefore, the City Council, to help the deserving poor and anyone else, has decided to establish a lending bank (Lehn Banco) with the following specification, such that everyone can as of now get funding there at a fair interest rate

The Hamburger Bank was the first Central Bank that both issued means of payments and provided at the same time Lombard loans to citizens and firms. Of course, this function would be contained if haircuts would be very high, or if the valuation of collateral submitted would be very low. Therefore, both were soon identified as important parameters. Article 23 of the Statute of the Monte di Pietà di Siena of 1472 specifies that the pledge needs to be worth "at least a third more than the amount that is lent", which implies a haircut of 25%. The Monte di Pietà in Bologna in 1514 (article 6 of the statutes) foresees already a differentiated haircut schedule (whereby the differentiation seems to be risk-based):

> And such a Custodian shall be bound to value the pledges faithfully and fairly. And if the pledges are of gold or silver, he shall lend according to the valuation of two parts of the pledge, and no more; but if they are robes or other things, he shall lend only half the valuation of such pledges.

The Statutes of the Monte di Pietà of Rome (1581, article 18) set collateral eligibility requirements by excluding only certain specific items:

> He shall lend money with regards to any type of stuff, except for offensive or defensive weapons, furs, grouped yarn, giving advice on gold and silver coated items that may be faulty and especially that the pledge will suffice

(2) Lending facilities of Monte di Pietà to support the financial liquidity of the economy (last decades of 15th century). The economic ex-ante effects of the lender of last resort function (LOLR) of Monte di Pietà is described in a surprisingly modern way by Cerreti (1752, 12-13), referring to the effects of the creation of the first Monte in Perugia in 1463:

> The public soon felt all its usefulness [...]. The trader who pressed to pay a bill of exchange would have perished for not daring to borrow a sum on his goods, for fear of undermining his credit, found in the Mont de Pitié a secret and assured resource that would make his fortune. For such a trader has gone bankrupt for several million, owing it only to the scandalous usury of a first loan of four or five thousand pounds. Individuals who previously bought only with reserve, fearing, if something went wrong, that they would be forced to borrow at high interest on their goods, or to sell them at a considerable loss, bought, thanks to the Mont de Pitiè, with more boldness and confidence, by the certainty of finding, if need be, money on the items purchased. Beyond a useful circulation of commerce[...]. This beneficent morning dew also spread over creditors and debtors, who both had the satisfaction, one of extinguishing his debt, the other of receiving his claim.

In other words, the existence of a public LOLR generally strengthens funding liquidity in a way that supports economic development. For example, the ECB justified collateral measures similarly over the last 10 years (see below).

(3) The Hamburger Bank as Lender of last resort in 1763. The Hamburger Bank acted as full-scale LOLR in 1763 and was probably the first comprehensive such Central Bank use of collateral policies to restore financial stability after the outbreak of a crisis (Bindseil 2020, Section 5.2, p. 144). In 1763 a major financial crisis swept through the entire northern European financial centres (originating mainly from Amsterdam; see e.g. Schnabel and Hyun Song, 2004). Many banking houses and merchants were on the brink of default. On 3 August, the Hamburger Bank announced that it would be ready to provide an exceptional amount of Lombard credit to bank houses of up to one million Mark Banco with a maximum duration of 6 months (indeed an exceptional amount compared to the usual end of year balances of Lombard loans). The 1 million Mark Banco were exhausted on 9 August, and the merchant banking houses then requested unlimited Lombard credit against precious metals. Moreover, the question arose of how to extend credit beyond the usual counterparties, i.e. in particular to ordinary merchants who were now subject to acute liquidity stress as financing through bills of exchange had broken down. (Soetbeer, 1886), also quoting text from 1763, reports that:

> Under these circumstances, the Senate of the City passed on 26 August the following message to the chamber of commerce 'He [the Senate] has directed, after the current economic developments and their sad consequences for the merchants and the public credit had begun, its thoughts towards the question, if no means and ways could be identified, to support, through collateralised lending against merchandise or other assets, some honest merchant, who is in principle solid, but because of the unexpected fall of other foreign and domestic merchants, is under stress to make timely payments according to his commitments'. To this was associated an invitation to submit one or the other feasible plan, if one could find such, and implement it. While recognising 'that it is difficult, to find a mean with the intended effects, which is not associated with many inconveniences' the plan of a Lombard facility managed by the Admiralty was submitted three days later.

The belief that debtors who are "solid but temporarily illiquid" are candidates for benefitting from the LOLR thus dates back to at least 1763. The Admiralty scheme consisted, according to Sieveking (1933) in the Bank lending to the Admiralty as of 8 September 1763 500,000 Mark Banco; the Admiralty itself acted as (principal) intermediary and lent the money to merchants against collateral (that the Bank would not have accepted). The Admiralty of Hamburg was the highest port authority, which was run by merchants and members of the City Council. A particularly broad collateral set was accepted. To access the Admiralty Lombard facility, the merchants had to get their goods taxed by sworn brokers and could borrow upon them up to two-thirds of the estimated value, at the moderate interest rate of 0.25 per cent per month. Twenty merchants took initially recourse to credit for a value of 287,000 Mark Banco, providing as collateral: oil, tobacco, sugar, coffee, etc. This credit provision was in addition to the standard Lombard facility of the Hamburger Bank, which itself reached high levels. Today, most economists associate Bagehot's Lombard Street of 1873 as being at the very origin of central banks' lender of last resort experience and awareness. However, it is interesting to note that for Bagehot the Bank of England was not unique, since he was explicitly referring to "other similar banks" (p. 87):

> [The Bank of England] must in time of panic do what all other similar banks must do; that in time of panic it must advance freely and vigorously to the public out of the reserve [...]. The end is to stay the panic; and the

> advances should, if possible, stay the panic. [...] these advances should be made on all good banking securities, and as largely as the public ask for them. The reason is plain. The object is to stay alarm, and nothing therefore should be done to cause alarm. But the way to cause alarm is to refuse someone who has good security to offer. The news of this will spread in an instant through all the money market at a moment of terror; no one can say exactly who carries it, but in half an hour it will be carried on all sides, and [P. 88] will intensify the terror everywhere [...]. The great majority, the majority to be protected, are the 'sound' people, the people who have good security to offer. If it is known that the Bank of England is freely advancing on what in ordinary times is reckoned a good security—on what is then commonly pledged and easily convertible—the alarm of the solvent merchants and bankers will be stayed. But if securities, really good and usually convertible, are refused by the Bank, the alarm will not abate, the other loans made will fail in obtaining their end, and the panic will become worse and worse.

In short, central banks must at least preserve collateral availability in financial crisis situations if they want to contribute to overcoming the crisis. They must not restrict their collateral framework, and they must not even let paper lose their eligibility in a crisis because e.g. liquidity or credit quality temporarily deteriorates.

(4) French railway companies in the 1850s. Already Kindleberger (1984) highlights the role of accepting railroad bonds as collateral by the Banque de France during the economic upswing in the 1850s ("The boom of the 1850s, for example, was by no means solely the result of the [gold] discoveries of 1849 and 1851. [...] The Credit Mobilier, first established in France in 1852, and later the action of the Banque de France in admitting railroad securities to discount in 1856, were of greater importance than the discoveries [...]")

According to (Leclercq, 1982), "After the coup which led to the 'Second Empire', the government asked the Banque de France to accept the railway companies' bonds and equities as collateral in discount operations and also for loans to any private person. It also asked the Banque de France to lend money to the railway companies ahead of new issuances and to place such issuances in the market. These measures helped the railway companies in financing their activities, at a time when they have faced constraints and had been prompted to merge among themselves by the government". These measures gave significant support to the development of railway companies in France at the time until these companies, weakened in particular by rather high debts, were later forced into mergers and nationalised. The measures included not only favourable treatment of the railway companies' bonds and stocks in the Banque de France's collateral framework, but also purchases of these bonds and stocks by the Banque de France. While the purchases likely played a significant role, the same applied to the collateral framework measures, as shown by the fact that the amounts of credit granted by the Banque de France and the amount of railway company bonds and stocks used as collateral increased significantly in the years following the abovementioned decisions, as reported in (Plessis, 1985, pp. 113-114). Further analysis related to the Banque de France's historical collateral framework can be found in Bignon and Jobst (2017).

(5) The German "Lombardverbot" for Russian Government bonds in 1887. In the 1880s, the "Lombardverbot", the ineligibility of Russian bonds as collateral in Reichsbank Lombard loans (Kindleberger, 1984, p. 227) would lead to major capital flows between Russia, France and Germany and would be one step amongst many towards WWI."In the German Foreign Office about this time, Herbert Bismarck, the Chancellor's son, proposed forbidding bank advances on Russian securities as an act of economic warfare [. . .] on 10 November 1887, an order was issued forbidding banks to lend on Russian securities – the famous Lombardverbot. Prices of Russian bonds fell further in Germany; some were bought back by Russian investors, a great many by French." The Lombardverbot was eventually lifted only on 26 October 1894. It however had a lasting impact on foreign debt allocation within Europe and contributed to making French investors the by far largest group of victims of the ultimate Russian default arising with the Red revolution.

(6) Lowering haircuts by Reichsbank in 1925 to support long term agricultural credit. Hjalmar Schacht mentions in his book about the stabilisation of the mark (Schacht, 1927) a number of measures undertaken by the Reichsbank in 1925 to support long term credit to agricultural enterprises. One of these measures was that "the Reichsbank accepted a considerable additional number of covered bonds as collateral for Lombard loans of the Reichsbank and increased the maximum loanable amount from 50% to 75% (i.e. lowered haircuts from 50% to 25%). The result was a surprising upwards movement of covered bond valuations, which supported the inflow of substantial additional new funds also from other investors to agriculture" (see also the Annual Report of the Reichsbank for 1925, page 9).

(7) Collateral measures to address the financial crisis in 2008. Before and even more after the default of Lehman, the large majority of central banks around the globe softened and broadened their collateral frameworks. In the words of the BIS Markets Committee (Committee et al., 2013, pp. 8-9):

> During the height of the financial crisis in 2008–09, a number of central banks introduced, to varying degrees, crisis management measures such

> as a temporary acceptance of additional types of collateral, a temporary lowering of the minimum rating requirements of existing eligible collateral or a temporary relaxation of haircut standards.

For example, the ECB announced such measures in a press release dated 15 October 2008. The Executive Board Member in charge of Market Operations at that time justified the measures in a speech of 10 November 2009 as follows (González-Páramo, 2009):

> Accordingly, the set of measures implemented by the Eurosystem – our enhanced credit support programme – were designed with the objective of providing support to the banking sector by: (a) helping the functioning of the money market, (b) easing funding conditions for banks, and (c) improving market liquidity in segments of the private debt securities market (specifically, the market for covered bonds) that represent an important source of funding for euro area banks. Through these measures, the ECB aimed to mitigate the risk of systemic illiquidity in the euro area banking sector and to guarantee a steady flow of banking credit to euro area households and firms.

These measures are both ex post measures, to address the tightening resulting from the crisis and to prevent defaults, as well as forward looking ex ante measures which want to encourage banks to provide fresh credit which would not be the intention of a pure emergency measure aiming at preventing acute bank defaults.

(8) ECB collateral measures to address sovereign debt crisis in Europe (2009-2015). Collateral availability can tighten without active measures by the Central Bank, for example if a deterioration of credit quality of important debt issuers leads to them losing eligible issuer status, or if they become subject to higher haircuts. This was an important challenge not only in the Lehman crisis, but also in the subsequent euro area Government debt crisis. While the ECB had lowered the general rating threshold in October 2008 from A- to BBB-, a number of countries subsequently fell below that lowered threshold, namely Greece, Portugal, and Cyprus. We focus below on the case if Greece. The measure was announced on 3 May 2010:

> The Governing Council of the European Central Bank (ECB) has decided to suspend the application of the minimum credit rating threshold in the collateral eligibility requirements for the purposes of the Eurosystem's credit operations in the case of marketable debt instruments issued or guaranteed by the Greek government. This suspension will be maintained until further notice. The Greek government has approved an economic and

> financial adjustment programme, which has been negotiated with the European Commission, in liaison with the ECB, and the International Monetary Fund. The Governing Council has assessed the programme and considers it to be appropriate. This positive assessment and the strong commitment of the Greek government to fully implement the programme are the basis, also from a risk management perspective, for the suspension announced herewith

Unfortunately, the Greek program eventually fell off-track and the ECB felt obliged on 4 February 2015 to suspend the waiver "as it [was] currently not possible to assume a successful conclusion of the programme review". The ECB re-instated the waiver for Greece on 22 June 2016, when it could again "acknowledge the commitment of the Greek government to implementing current ESM programme and expects continued compliance with its conditionality". In the meantime, Greece went through a period of bank holidays and capital controls which became necessary as the Greek government did not comply with EU/IMF program conditionality and fuelled discussions on an exit of Greece from the Euro area. Financing conditions were of course highly unfavourable for Greek firms during this episode.

(9) ECB collateral measures to address the COVID crisis – monetary policy at the zero-lower bound. Facing the COVID-2019 crisis, a number of central banks relaxed their collateral framework, despite the fact that credit quality of issuers and counterparties did not improve. As an example, the *unprecedented* package announced on 7 April 2020 by ECB includes a general reduction of the credit operations haircuts (from ECB Press release):

> The Governing Council of the European Central Bank (ECB) today adopted a package of temporary collateral easing measures to facilitate the availability of eligible collateral for Eurosystem counterparties to participate in liquidity providing operations[...]. The Eurosystem is increasing its risk tolerance to support the provision of credit via its refinancing operations, particularly by lowering collateral valuation haircuts for all assets consistently[...]. the Governing Council decided to temporarily increase its risk tolerance level in credit operations through a general reduction of collateral valuation haircuts by a fixed factor of 20%.

Indeed, the Covid crisis and the associated market volatility created exceptional collateral (*margining*) requirements by CCPs, which put banks under stress, and which made the ability to rely on the Central Bank for sourcing liquidity particularly important (see e.g. ISDA, 2021). Moreover, the ECB had reached the effective lower bound to its interest rate setting already from 2014 to 2019, when the still valid rate of the

	Monetary Policy	Liquidity (ex ante)	Financial Stability (ex post)	Structural Industrial policy	Market failure	Social policy	Other policy
(1) Monte di Pietà 1463		X				X	
(2) Hamburg, 1619		X				X	
(3) Hamburger Bank, 1763			X				
(4) French Railways, 1850s				X			
(5) German Lombardverbot, 1887							Foreign
(6) Reichsbank covered bonds 1925				X			
(7) Lehman crisis of 2008		X	X				
(8) Sovereign debt crisis 2009-2015	X		X				
(9) ECB Covid19 -2020	X	X	X				
(10 ECB Climate change 2021					X		Environment

Figure A.1: A schema classifying the ten examples across history of central banks in six classes according to the pursued policy goals.

deposit facility of -0.5% was reached. In such a context, as the model of Bindseil and Lanari (2022), the lowering of haircuts can have similar effects on monetary conditions as a lowering of interest rate have.

(10) ECB collateral measures to address climate change. Last but not least, central banks (ECB, 2021), NGOs (Dafermos et al., 2021) and academics (Shoenmaker, 2019) have identified the collateral framework as important instrument in supporting the transition to a more climate friendly economy. In July 2021, the ECB launched an *action plan* to include climate related considerations into the definition and implementation of its monetary policy

> Within the mandate of the ECB, the climate change agenda will affect the collateral framework in two fundamental aspects. First, disclosure requirements for private sector assets will be introduced as a new eligibility criterion or as a basis for a differentiated treatment for collateralized credit. Second, haircuts modelling and calibration will reflect all relevant risks, including those related to climate change. Third, the ECB committed to support actively innovation in the area of sustainable finance, accepting sustainability-linked bonds as collateral.

Appendix B. Deleveraging and liquidity-stress management with multiple funding sources and discrete assets classes

In this section we discuss the role of banks behaviours in a financial market with discrete asset classes. These classes feature different liquidity levels along several dimensions, any of this dimensions being identified by the potential use case for each unit of asset. Since in the presented framework assets can be mobilized within different channels and serve diverse bank's objectives, the adopted modelling alternatives for banks' allocation choices may affect the outcome of the stress test.

That the assumptions on how agents choose to mobilize assets have a significant impact on stress testing outcomes has already been noticed by Coen et al. (2019) in a model of deleveraging through fire sales only. In that context, two main perspectives span the sets of modelling assumptions. The first assumes that banks deleverage their assets following simple heuristics, usually selling proportionally across asset classes (Greenwood et al., 2015; Cont and Schaanning, 2017a; Duarte and Eisenbach, 2021). In practical terms, if a bank with holdings of 10% in bonds, 30% in ABSs and 60% in loans needs to sell 10 units on the market, she will try to sell 1 unit of bonds, 3 of ABSs and 6 of loans. The second assumption states that financial institutions determine a pecking order of the asset classes (Braouezec and Wagalath, 2018, 2019; Coen et al., 2019; Bindseil and Lanari, 2022), usually maximizing the expected liquidation value or other performance indicator associated to the allocation vector.

Comparing the two perspectives in a pure-sales framework, Coen et al. (2019) show that a system where banks adopt proportional selling might suffer systemic losses five times larger then a system where banks optimize over the possible liquidation strategies, this happens because agents sell large amounts of illiquid assets even when they could gather the needed liquidity relying on their high quality instruments. However, the optimization approach to the banks' allocation problem seems to be viable only in simple models where the options and the objectives are limited and controlled. In a system where banks can sell or pledge their assets, for example, the model of Bindseil and Lanari (2022) derive optimization results only when liquidity is a one dimensional property on a continuous interval. When that hypothesis is relaxed, with four liquidity classes and assuming that assets in each class are pledged or collateralized in full, Bindseil et al. (2017b) show that any dominant strategy does not emerge within the strategy space.

For what concern our operational model, we endorse the perspective of agents based models (ABMs) and represent banks as agents that follow agents-specific behavioural rules. Among the possible behaviours, the modellers can opt for analytical or computational optimization — if and when the optimization problem is well defined and admit solutions — or rather heuristics that represent realistic behavioural patterns. Moreover, we show here how the general setting outlined in the previous section defines a liquidity environment whose state configuration is characterized by a high degree of complexity and Knightian uncertainty, for two reasons mainly. First, some of the key parameters for the strategies' evaluation are known to the agents only after their decision is taken. This happens because banks are price taker and decide to sell part of their assets facing a discount on the initial price that depends on the strategy of the other financial institutions, through the total amount sold. Second, the actions of the banks have an effect on an intertemporal dimension: encumbering assets through any of the available channels might be the best solution at a certain time step, but the encumbered collateral might worth more for the bank if mobilized later as the liquidity landscape changes.

Here we provide an overview of the banks liquidity-stress management in the framework outlined by our operational model. Thus, we consider the general allocation problem for the portfolio of assets of a single bank accessing to three funding sources (assets sales, Central Bank collateralized credit and the repo market), facing possible liquidity shortfall and targeting a set of three capital and liquidity requirements. Notice that not all the constraints are uniformly binding in any scenario. Onn one side, some of the requirements might be overlooked by the bank during the (short-term) horizon of a financial crisis, e.g. when the regulation is relaxed at the crisis outbreak, while on the other side, banks might aim at over-compliance for certain regulatory requirements. This is the case of financial institutions targeting a capital ratio (RWCR) or a LCR well above the required threshold (see e.g. Grandia et al., 2019, for the LCR). In our framework, this means that the banks might want to acess the various funding sources to restore their fundamentals even when they comply with the regulatory requirements and do not face any liquidity shortfall[42].

Formally, consider a bank facing a total liquidity shortfall of $\lambda_i \geq 0$ and with leverage ratio LR_i, liquidity coverage ratio LCR_i and risk weighted capital RWCR_i. In a market environment as that defined in Section 2. We define an allocation strategy as the set of vectors:

$$\mathbf{x}_i = (\mathbf{s}_i, \mathbf{p}_i^{RP}, \mathbf{p}_i^{CB}) = (\mathbf{s}_i, \mathbf{p}_i^{RP}, \mathbf{p}_i^{CB})$$

where each vector collect the share of unencumbered assets allocated to the sales, the repo market and the Central Bank credit operations. The dimensionality of the problem in considerably high, but it reduces after few simple considerations: i) non

[42] A thorough analysis of this issue is out of the scope of this work. Notice however that the proposed framework is flexible enough to model the bank's strategic recourse to the Central Bank's credit with the aim to restyle their regulatory requirements. Empirical evidence on their behaviours and their effect on monetary policy implementation has been collected recently in Grandia et al. (2019) and Kedan and Veghazy (2021) among the others.

marketable assets are not available to be sold and are not accepted as collateral in the repo operations and ii) the overall sum of shares needs to stay below one. This means that after a further breakdown of the vectors $\mathbf{s}_i = (\mathbf{s}_i^M, \mathbf{s}_i^N)$, $\mathbf{p}_i^{RP} = (\mathbf{p}_i^{RP,M}, \mathbf{p}_i^{RP,N})$, the set of possible solutions restricts to

$$\mathcal{S}_i = \left\{\mathbf{x}_i \,|\, s_{\nu,i}^N, p_{\nu,i}^N = 0,\ s_{\mu,i}^M + p_{\mu,i}^M + p_{\mu,i}^M \leq 1\ ,\ p_{\nu,i}^N \leq 1\right\}$$

As anticipated, covering possible liquidity shortfall might not be the unique purpose of a financial institution. In general, she might be willing to drive all or some of their liquidity and capital indicator values above certain threshold[43]: $\varphi_i^{LR}, \varphi_i^{LCR}, \varphi_i^{RWCR}$. Thus the general problem consists of selecting one point in the space defined by the set of equations[44]:

$$\begin{aligned} & v_S(\mathbf{x_i}) + v_{CB}(\mathbf{x_i}) + v_{RP}(\mathbf{x_i}) \geq \lambda_i \\ & \underline{e}(\mathbf{x}_i) \geq 0 \\ & \underline{\mathrm{LR}}(\mathbf{x}_i) \geq \varphi_i^{LR},\ \underline{\mathrm{LCR}}(\mathbf{x}_i) \geq \varphi_i^{LCR},\ \underline{\mathrm{RWCR}}(\mathbf{x}_i) \geq \varphi_i^{RWCR} \end{aligned} \tag{B.1}$$

where the first line is the sum of the liquidity collected along the three channels, while the other two encode the constraints on equity and on the regulatory ratios. The system (B.1) defines the set of viable allocations as the set of points $\mathcal{V}_i \subset \mathcal{S}_i$, satisfying (B.1).

At this stage one can impose the agents to search for an optimal strategy in the sense that it maximizes the ex post equity ($\underline{e}(\mathbf{x}_i)$), while fulfilling the other constraints. This is possible in the current setting only after neglecting the endogeneity associated with fire sales discounts[45]. Here we focus rather on the analysis of the space of the viable strategies to show how optimality may be ill defined in a context of market interactions.

One of the strengths of our framework is that the dynamics of the stress scenario unfold even when agents do not perceive the regulatory requirements as binding and, in general, it allows to model a wide heterogeneity of behaviours, for example: i) banks overlooking regulatory requirements when dealing with liquidity shortfalls and adjusting the values for the ratios only when not in liquidity need; ii) banks operating in the liquidity market for restyling the ratio event when their are above the threshold. In the remainder of this section we show how any maximization problem defined on

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[43] As noted above, the reference values for the threshold might be imposed by the regulatory authorities or rather being subjectively determined by the agents.

[44] Note again here that we define the updated quantities using the underlined notation and that throughout this section we explicit their dependence from the strategy vector $\mathbf{x}_i$.

[45] Indeed, Coen et al. (2019) replace the vector of total sales $\mathbf{q}$ in (13) (whose elements are $q_\mu = \sum_j A_{\mu,j}^{M,une} s_{\mu,j}^M$), with the vector of sales of the the bank i. An other option consists of modelling a complete strategic game and has been applied to a context of fire sales only in Braouezec and Wagalath (2019).

the space of viable strategies $\mathcal{V}_i$ is ill-defined in a context of discrete asset classes and multiple funding sources for three main reasons. We conclude providing a brief presentation of the algorithm that we implemented for the applications of the model in the next section[46].

A rugged strategy space. The first is that even choosing a single performance indicator for a strategy $\mathbf{x}_i$, analytical maximization is not an option and computational maximization is unfeasible in $\mathcal{V}_i$, because any process of grid search scales with the dimension of the space (the number of assets categories) and other search algorithm are likely to get stuck in a local maximum since the viable-strategy space is rugged. Consider the equity implied by a chosen strategy $\underline{e}_i(\mathbf{x}_i)$ as a first measure of the performance and calculate its value for one hundred thousand points (of $\mathcal{V}_i$). After choosing a reference point and a suitable metrics the viable-strategies space can be rendered in a 3D surface plot as shown in Fig. B.1. With a simple visual inspection of

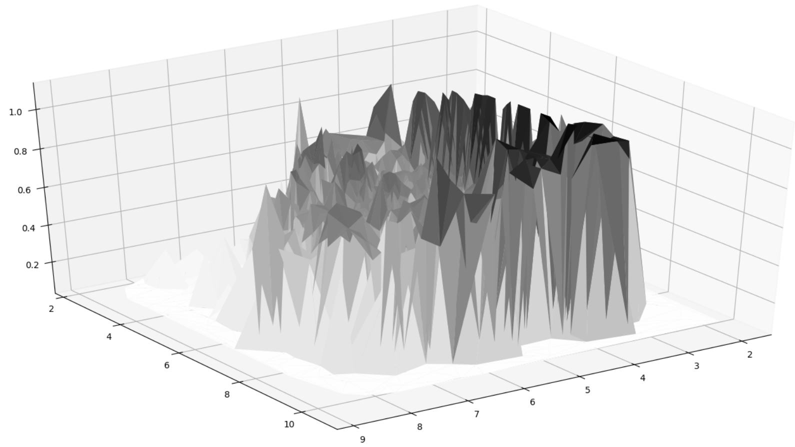

Figure B.1: The rugged implied equity landscape of the viable-strategies subspace for a generic bank. On the x-y plane points represent the Canberra distance of each strategy component from a fixed reference strategy. On the z-axis the implied equity relative to the initial equity is reported.

the plot it can be noticed that the space seems to have the basic characteristics of a rugged landscape (Levinthal and Warglien, 1999) and it is confirmed when we consider some basic topological measure. Look for example at the density of the locally optimal strategies. To get a proxy one can look at the share of strategies reducing the equity of one percent 1% within the strategy reducing the equity of the 5%, therein the density

[46] As already mentioned the model can be adapted to any form of strategy definition or search, including proportional deleveraging. Moreover different agents can implement different exploration behaviours.

of the strategies is just the 0.85% (on average across the tested banks)[47]. On the same line, the histogram in the top left-corner of Fig. B.2 shows exactly how strategies are increasingly rare as we restrict to those that minimize equity loss.

Multiple performance indicators. The second reason against a maximizing approach is that agents might pursue multiple objectives while seeking liquidity. They might want to reduce equity losses but also preserve liquid assets to cover potential future losses in the development of the crisis. Fig. B.2 gives a first insight on this issue. While some performance indicators display high level of correlations, as the case of RWCR loss and equity loss, other might have low or absent correlation, meaning that it would be unfeasible to maximize along a direction while preserving the rest. For example the same bank willing to minimize her equity will try to sell or pledge the most liquid assets (in terms of market depths). Indeed, assets with high market depths are likely to get lower discounts and imply lower equity losses. However this naturally leads to a decline in the liquidity potential of the portfolio of disposable assets of the bank.

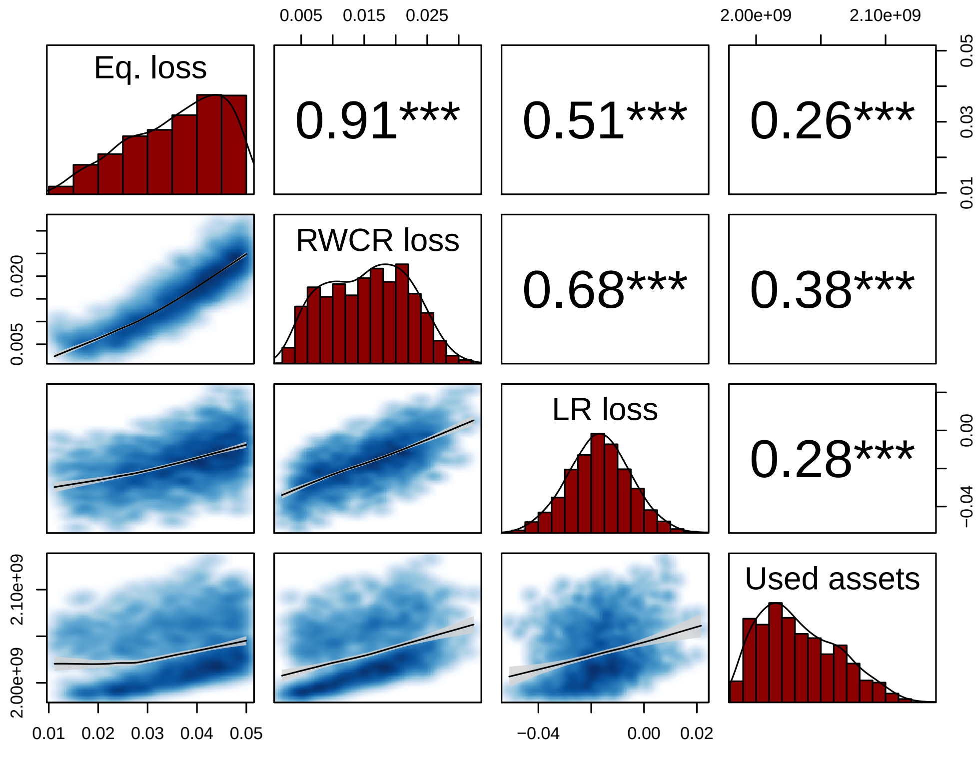

Figure B.2: Performance of the tested strategies along four dimensions defined by four selected performance indicators: equity loss, RWCR loss, LR loss and HQ used assets. Comparison for a sample of ten thousands tested strategies for 80 banks facing a fixed liquidity shortfall of 5% of total assets.

[47] For this experiment we tested all the banks inizialized according to the simulated model described in the section below imposing a fixed liquidity shortfall of the 5% of total assets.

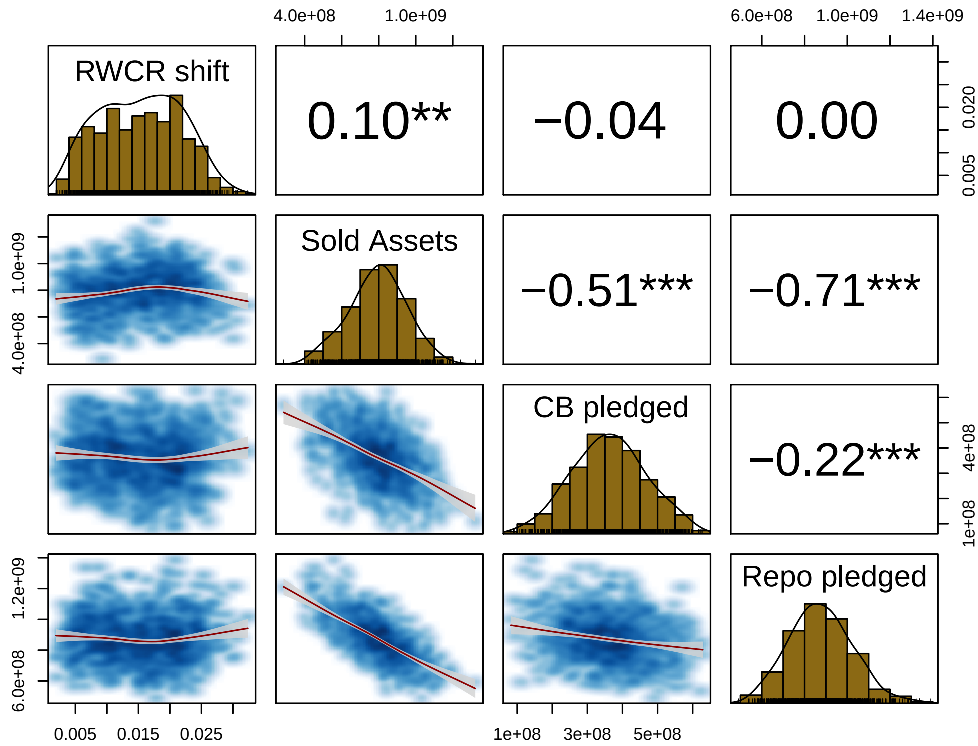

Figure B.3: RWCR shift compared with three different assets destination for diverse funding sources
Comparison for a sample of ten thousands tested strategies for 80 banks facing a fixed liquidity shortfall of 5% of total assets.

Strategies in a changing environment and an endogenously determined liquidity landscape. The third reason we discuss concerns the impossibility to set up a maximization problem when the parameters defining the problem change within the same step of the timeline of the events and in an inter-temporal dimension. Fig. B.4 shows the comparison between the effective market discounts (shaped dots) and the discounts estimated by the different agents while deleveraging. Expected discounts are computed replacing the quantity of total assets sold in the market with the quantity that the single banks is prepared to sell, namely using the sum at the numerator of Eq. 12 in place of the quantity defining each strategy (the vector $\mathbf{s}_i$ in the notation introduced above). The boxplots represent the distributions of the expected discounts for the banks populating a stylized financial environment (see section 3 below) for six selected asset classes. It is clear that even if the banks are informed on the market depths they can hardly predict what will be the outcome of the strategy when the effective discounts depend on the strategy of other banks. Notice that even strategies trying to predict the market discounts using past values are likely to underestimate the losses implied by market discounts, especially in the first stages of the crisis where the great part of the losses imputed to the stress test are concentrated.

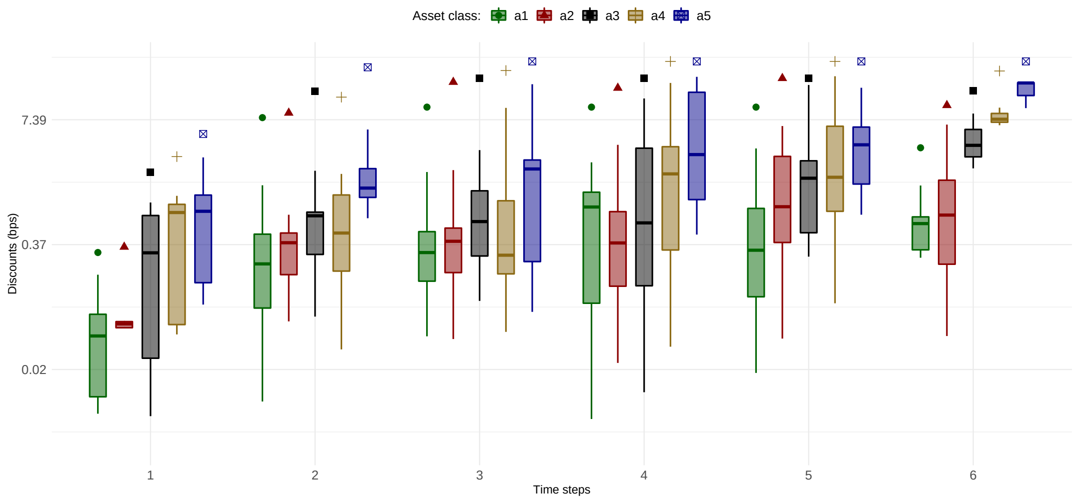

Figure B.4: A comparison of effective assets value discounts (shaped dots) with assets value discounts expected by single banks (boxplot of the distribution) for six time steps and six selected assets categories.

Local search with simple heuristics. We sketch in this paragraph a simple search algorithm within the strategy space, building on the results by Coen et al. (2019). Even though the simplifying assumptions of their work do not hold for the proposed framework, we use their results as a reference point for a local exploration of the strategy space of each bank. Formally, any bank finding herself in need of liquidity for a quantity λ, accessing the available funding sources through the following steps

1. Collect all the disposable marketable and non-marketable assets (i.e. excluding encumbered assets on assets that cannot be mobilized).

2. Order the assets i) by market depth (D_μ), ii) by the ratio between the market depths and the available amount $\left(\frac{D_\mu}{A_\mu^{M,une}}\right)$, iii) by the risk-weighted ratio $\rho_\mu \left(1 + \frac{D_\mu}{A_\mu^{M,une}}\right)$[48]. Notice here that our orderings while defined for marketable assets, can also include non-marketable assets with null market depth.

3. Given the liquidity need λ, define an allocation quantity for each asset class v_μ using the proportional deleveraging rule, i.e.

$$u_\mu(A_\mu^{M,une}) = \frac{A_\mu^{M,une}}{\sum_\mu A_\mu^{M,une} + \sum_\nu A_\nu^{N,une}} \lambda$$

$$u_\mu(A_\mu^{M,une}) = \frac{A_\mu^{M,une}}{\sum_\mu A_\mu^{M,une} + \sum_\nu A_\nu^{N,une}} \lambda$$

4. For any order defined at point 2, the bank takes that ordering and its reverse. This defines six orderings of the asset classes. For any of these orderings, starting

[48] Details on the rationale for this orderings can be found in Coen et al. (2019).

from the first asset class the quantity selected at point 3 is picked and a share at random $\alpha\, u_\mu$ is sold in the market, while the remainder $(1-\alpha)\, u_\mu$ is mobilized to get credit against collateral. The bank chooses to borrow from the Central Bank or in the private market comparing the haircuts and opting for the channel where the liquidity for unit of collateral is higher. The bank stops when she gets the needed liquidity λ or when the disposable assets are exhausted. This step is implemented H times, where H defines the search depth, anytime selecting different combination of α. Notice that for non-marketable assets α is set to zero by default.

5. Collect all the strategies and selects the one with minimal equity loss. If many strategies are equivalent according to the equity loss, then strategies with minimal sold assets and minimal used assets are preferred.

Appendix C. Summary statistics

	Mean	SD	Min	25%	50%	75%	Max
Tot. Asset (Bl)	278.01	432.05	3.92	48.02	90.96	286.03	2369.64
Tot. Liabilities (Bl)	260.61	407.67	3.52	44.83	81.90	269.73	2247.27
Equity (Bl)	17.40	24.77	0.24	3.41	6.27	17.01	122.37
CET1 (Bl)	15.38	21.40	0.21	3.14	5.85	14.84	100.26
CET1 ratio (%)	16.93	4.72	11.12	13.70	15.73	18.49	36.28
LCR (bp)	235.32	126.15	123.94	162.86	196.42	261.15	946.05
Leverage ratio (%)	6.70	2.42	4.02	5.16	5.94	7.26	15.50

Table C.1: Summary statistics for aggregate balance sheets. Source: authors computations on supervisory data

Category	Classification	Type	Counterpart	Value (Bl)	Share (%)
Asset	Non-tradable	Debt instruments	Central bank	32.53	0.26
Asset	Non-tradable	Debt instruments	Credit institutions	278.42	2.22
Asset	Non-tradable	Debt instruments	Government	1159.88	9.26
Asset	Non-tradable	Debt instruments	Non-financial institutions	90.50	0.72
Asset	Non-tradable	Debt instruments	Other financial institutions	159.22	1.27
Asset	Non-tradable	Derivatives	Credit institutions	35.79	0.29
Asset	Non-tradable	Derivatives	Other	1.73	0.01
Asset	Non-tradable	Derivatives	Other financial institutions	19.01	0.15
Asset	Non-tradable	Equity	Credit institutions	9.05	0.08
Asset	Non-tradable	Equity	Non-financial institutions	19.36	0.15
Asset	Non-tradable	Equity	Other	1.29	0.01
Asset	Non-tradable	Equity	Other financial institutions	37.83	0.30
Asset	Non-tradable	Loans	Central bank	131.79	1.06
Asset	Non-tradable	Loans	Credit institutions	614.04	4.90
Asset	Non-tradable	Loans	Government	408.91	3.26
Asset	Non-tradable	Loans	Households	4473.88	35.68
Asset	Non-tradable	Loans	Non-financial institutions	4182.21	33.35
Asset	Non-tradable	Loans	Other financial institutions	883.60	7.05

Table C.2: Composition of non-tradable assets. Source: authors computations on supervisory data

Category	Classification	Type	Counterpart	Value (Bl)	Share (%)
Asset	Tradable	Debt instruments	Central bank	3.67	0.16
Asset	Tradable	Debt instruments	Credit institutions	29.65	1.32
Asset	Tradable	Debt instruments	Government	279.25	12.45
Asset	Tradable	Debt instruments	Non-financial institutions	38.76	1.73
Asset	Tradable	Debt instruments	Other financial institutions	30.69	1.37
Asset	Tradable	Derivatives	Credit institutions	592.03	26.40
Asset	Tradable	Derivatives	Other	200.00	8.92
Asset	Tradable	Derivatives	Other financial institutions	309.55	13.80
Asset	Tradable	Equity	Credit institutions	18.85	0.84
Asset	Tradable	Equity	Non-financial institutions	179.59	8.01
Asset	Tradable	Equity	Other	0.24	0.01
Asset	Tradable	Equity	Other financial institutions	43.38	1.93
Asset	Tradable	Loans	Central bank	34.70	1.55
Asset	Tradable	Loans	Credit institutions	190.49	8.50
Asset	Tradable	Loans	Government	13.35	0.59
Asset	Tradable	Loans	Households	0.47	0.03
Asset	Tradable	Loans	Non-financial institutions	47.09	2.10
Asset	Tradable	Loans	Other financial institutions	231.09	10.31

Table C.3: Composition of tradable assets. Source: authors computations on supervisory data

Category	Classification	Type	Counterpart	Value (Bl)	Share (%)
Asset	Non-tradable	Debt instruments	Central bank	15.86	0.42
Asset	Non-tradable	Debt instruments	Credit institutions	133.30	3.56
Asset	Non-tradable	Debt instruments	Government	583.71	15.60
Asset	Non-tradable	Debt instruments	Non-financial institutions	43.60	1.16
Asset	Non-tradable	Debt instruments	Other financial institutions	89.10	2.38
Asset	Non-tradable	Equity	Credit institutions	3.15	0.08
Asset	Non-tradable	Equity	Non-financial institutions	5.02	0.13
Asset	Non-tradable	Equity	Other	0.44	0.01
Asset	Non-tradable	Equity	Other financial institutions	11.03	0.29
Asset	Non-tradable	Loans	Central bank	28.25	0.75
Asset	Non-tradable	Loans	Credit institutions	195.45	5.22
Asset	Non-tradable	Loans	Government	137.45	3.67
Asset	Non-tradable	Loans	Households	1113.79	29.76
Asset	Non-tradable	Loans	Non-financial institutions	664.55	17.76
Asset	Non-tradable	Loans	Other financial institutions	236.88	6.33
Asset	Tradable	Debt instruments	Central bank	1.82	0.05
Asset	Tradable	Debt instruments	Credit institutions	15.57	0.42
Asset	Tradable	Debt instruments	Government	177.73	4.75
Asset	Tradable	Debt instruments	Non-financial institutions	25.10	0.67
Asset	Tradable	Debt instruments	Other financial institutions	19.11	0.51
Asset	Tradable	Equity	Credit institutions	11.83	0.32
Asset	Tradable	Equity	Non-financial institutions	108.80	2.91
Asset	Tradable	Equity	Other	0.07	0.00
Asset	Tradable	Equity	Other financial institutions	26.12	0.70
Asset	Tradable	Loans	Central bank	6.27	0.17
Asset	Tradable	Loans	Credit institutions	42.75	1.14
Asset	Tradable	Loans	Government	3.42	0.09
Asset	Tradable	Loans	Households	0.12	0.00
Asset	Tradable	Loans	Other financial institutions	42.52	1.14

Table C.4: Composition of encumbered assets. Source: authors computations on supervisory data

Category	Classification	Type	Counterpart	Value (Bl)	Share (%)
Asset	Non-tradable	Debt instruments	Central bank	16.67	0.17
Asset	Non-tradable	Debt instruments	Credit institutions	145.12	1.48
Asset	Non-tradable	Debt instruments	Government	576.17	5.86
Asset	Non-tradable	Debt instruments	Non-financial institutions	46.90	0.48
Asset	Non-tradable	Debt instruments	Other financial institutions	70.12	0.71
Asset	Non-tradable	Equity	Credit institutions	5.90	0.06
Asset	Non-tradable	Equity	Non-financial institutions	14.34	0.15
Asset	Non-tradable	Equity	Other	0.85	0.01
Asset	Non-tradable	Equity	Other financial institutions	26.80	0.27
Asset	Non-tradable	Loans	Central bank	103.54	1.05
Asset	Non-tradable	Loans	Credit institutions	418.59	4.26
Asset	Non-tradable	Loans	Government	271.46	2.76
Asset	Non-tradable	Loans	Households	3360.09	34.17
Asset	Non-tradable	Loans	Non-financial institutions	3517.66	35.77
Asset	Non-tradable	Loans	Other financial institutions	646.72	6.58
Asset	Tradable	Debt instruments	Central bank	1.85	0.02
Asset	Tradable	Debt instruments	Credit institutions	14.08	0.14
Asset	Tradable	Debt instruments	Government	101.52	1.03
Asset	Tradable	Debt instruments	Non-financial institutions	13.66	0.14
Asset	Tradable	Debt instruments	Other financial institutions	11.58	0.12
Asset	Tradable	Equity	Credit institutions	7.02	0.07
Asset	Tradable	Equity	Non-financial institutions	70.79	0.72
Asset	Tradable	Equity	Other	0.17	0.00
Asset	Tradable	Equity	Other financial institutions	17.26	0.18
Asset	Tradable	Loans	Central bank	28.43	0.29
Asset	Tradable	Loans	Credit institutions	147.74	1.50
Asset	Tradable	Loans	Government	9.93	0.10
Asset	Tradable	Loans	Households	0.35	0.00
Asset	Tradable	Loans	Other financial institutions	188.57	1.92

Table C.5: Composition of unencumbered assets. Source: authors computations on supervisory data

Country	Value (Bl)	Share (%)
AT	185.11	1.58
AU	82.11	0.70
BE	448.62	3.84
CA	81.43	0.70
CH	70.94	0.61
CN	64.41	0.55
CY	12.53	0.11
DE	1545.48	13.21
DK	132.62	1.13
EE	6.06	0.05
ES	1067.81	9.13
FI	152.37	1.30
FR	1445.82	12.36
GB	1028.20	8.79
GR	137.68	1.18
HK	35.18	0.30
IE	159.90	1.37
IT	1041.96	8.91
JP	145.20	1.24
KR	50.01	0.43
LT	7.46	0.06
LU	193.74	1.66
LV	3.52	0.03
MT	6.02	0.05
NL	765.11	6.54
NO	78.54	0.67
NZ	3.28	0.03
PT	172.96	1.48
RU	33.14	0.28
RW	1359.27	11.62
SE	125.35	1.07
SG	42.81	0.37
SI	14.94	0.13
SK	62.58	0.54
US	933.59	7.98

Table C.6: Composition of assets by country of counterpart (RW = Rest of the World). Source: authors computations on supervisory data

Country	Value (Bl)	Share (%)
AT	131.26	3.14
AU	10.40	0.25
BE	175.54	4.20
CA	14.48	0.35
CH	47.54	1.14
CN	2.85	0.07
CY	8.85	0.21
DE	562.98	13.46
DK	40.87	0.98
EE	4.80	0.11
ES	485.52	11.61
FI	117.96	2.82
FR	626.50	14.98
GB	169.23	4.05
GR	57.32	1.37
HK	15.92	0.38
IE	59.77	1.43
IT	532.45	12.73
JP	69.65	1.67
KR	2.46	0.06
LT	4.62	0.11
LU	115.51	2.76
LV	2.28	0.05
MT	2.35	0.06
NL	360.85	8.63
NO	5.57	0.13
NZ	0.12	0.00
PT	69.01	1.65
RU	12.51	0.30
RW	180.98	4.33
SE	17.10	0.41
SG	11.53	0.28
SI	10.06	0.24
SK	26.93	0.64
US	226.41	5.41

Table C.7: Composition of loans to non-financial corporations by country of counterpart (RW = Rest of the World). Source: authors computations on AnaCredit

Prob. of default	Value (Bl)	Share (%)
<0.1	3477.82	83.16
>=0.1 and <0.4	90.39	2.16
>=0.4	134.00	3.20
ND	479.99	11.48

Table C.8: Composition of loans to non-financial corporations by probability of default. Source: authors computations on AnaCredit

Maturity	Value (Bl)	Share (%)
<3 years	1996.55	47.74
>=3 and <7 years	1020.58	24.40
>=7 years	1165.09	27.86

Table C.9: Composition of loans to non-financial corporations by maturity. Source: authors computations on AnaCredit

NACE Code (Lv.2)	Description	Value (Bl)	Share (%)
1	Crop and animal production, hunting and related service activities	49.68	1.19
2	Forestry and logging	2.53	0.06
3	Fishing and aquaculture	1.82	0.04
5	Mining of coal and lignite	0.41	0.01
6	Extraction of crude petroleum and natural gas	13.33	0.32
7	Mining of metal ores	3.84	0.09
8	Other mining and quarrying	3.96	0.09
9	Mining support service activities	4.10	0.10
10	Manufacture of food products	67.56	1.62
11	Manufacture of beverages	12.57	0.30
12	Manufacture of tobacco products	1.05	0.03
13	Manufacture of textiles	8.85	0.21
14	Manufacture of wearing apparel	6.09	0.15
15	Manufacture of leather and related products	4.90	0.12
16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	10.25	0.25
17	Manufacture of paper and paper products	14.44	0.35
18	Printing and reproduction of recorded media	5.14	0.12
19	Manufacture of coke and refined petroleum products	14.75	0.35
20	Manufacture of chemicals and chemical products	29.88	0.71
21	Manufacture of basic pharmaceutical products and pharmaceutical preparations	12.24	0.29
22	Manufacture of rubber and plastic products	19.97	0.48
23	Manufacture of other non-metallic mineral products	17.11	0.41
24	Manufacture of basic metals	29.24	0.70
25	Manufacture of fabricated metal products, except machinery and equipment	40.23	0.96
26	Manufacture of computer, electronic and optical products	17.82	0.43
27	Manufacture of electrical equipment	18.17	0.43
28	Manufacture of machinery and equipment n.e.c.	36.41	0.87
29	Manufacture of motor vehicles, trailers and semi-trailers	42.29	1.01
30	Manufacture of other transport equipment	15.06	0.36
31	Manufacture of furniture	5.74	0.14
32	Other manufacturing	10.87	0.26
33	Repair and installation of machinery and equipment	15.53	0.37
35	Electricity, gas, steam and air conditioning supply	141.14	3.37
36	Water collection, treatment and supply	9.25	0.22
37	Sewerage	4.72	0.11
38	Waste collection, treatment and disposal activities; materials recovery	10.94	0.26
39	Remediation activities and other waste management services	0.59	0.01
41	Construction of buildings	106.94	2.56
42	Civil engineering	22.31	0.53
43	Specialised construction activities	39.32	0.94
45	Wholesale and retail trade and repair of motor vehicles and motorcycles	50.55	1.21
46	Wholesale trade, except of motor vehicles and motorcycles	215.76	5.16
47	Retail trade, except of motor vehicles and motorcycles	98.02	2.34
49	Land transport and transport via pipelines	43.57	1.04
50	Water transport	31.96	0.76
51	Air transport	11.06	0.26
52	Warehousing and support activities for transportation	47.53	1.14
53	Postal and courier activities	9.66	0.23
55	Accommodation	58.58	1.40
56	Food and beverage service activities	27.61	0.66
58	Publishing activities	8.72	0.21
59	Motion picture, video and television programme production, sound recording and music publishing activities	4.57	0.11
60	Programming and broadcasting activities	1.68	0.04
61	Telecommunications	27.41	0.66
62	Computer programming, consultancy and related activities	23.82	0.57
63	Information service activities	6.63	0.16
64	Financial service activities, except insurance and pension funding	1038.52	24.83
65	Insurance, reinsurance and pension funding, except compulsory social security	117.57	2.81
66	Activities auxiliary to financial services and insurance activities	130.28	3.12
68	Real estate activities	600.88	14.37
69	Legal and accounting activities	12.47	0.30
70	Activities of head offices; management consultancy activities	250.32	5.99
71	Architectural and engineering activities; technical testing and analysis	17.70	0.42
72	Scientific research and development	3.88	0.09
73	Advertising and market research	5.44	0.13
74	Other professional, scientific and technical activities	10.20	0.24
75	Veterinary activities	0.90	0.02
77	Rental and leasing activities	78.28	1.87
78	Employment activities	4.35	0.10
79	Travel agency, tour operator and other reservation service and related activities	5.27	0.13
80	Security and investigation activities	1.79	0.04
81	Services to buildings and landscape activities	6.85	0.16
82	Office administrative, office support and other business support activities	47.71	1.14
84	Public administration and defence; compulsory social security	6.25	0.15
85	Education	8.25	0.20
86	Human health activities	30.84	0.74
87	Residential care activities	12.44	0.30
88	Social work activities without accommodation	3.67	0.09
90	Creative, arts and entertainment activities	1.74	0.04
91	Libraries, archives, museums and other cultural activities	1.63	0.04
92	Gambling and betting activities	2.74	0.07
93	Sports activities and amusement and recreation activities	10.97	0.26
94	Activities of membership organisations	4.37	0.10
95	Repair of computers and personal and household goods	0.67	0.02
96	Other personal service activities	10.58	0.25
97	Activities of households as employers of domestic personnel	0.22	0.01
98	Undifferentiated goods- and services-producing activities of private households for own use	0.09	0.00
99	Activities of extraterritorial organisations and bodies	1.58	0.04

Table C.10: Composition of loans to non-financial corporations by economic sector. Source: authors computations on AnaCredit

Category	Type	Counterpart	Value (Bl)	Share (%)
Liability	Debt instruments	Central bank	1595.25	9.04
Liability	Deposit	Credit institutions	270.47	1.53
Liability	Deposit	Households	4702.59	26.65
Liability	Deposit	Non-financial institutions	2502.15	14.18
Liability	Deposit	Other finanacial institutions	772.63	4.38
Liability	Deposit (agreed maturity)	Households	535.95	3.04
Liability	Government	Deposit	411.34	2.33
Liability	Other		2318.93	13.14
Liability	Repo		741.05	4.20
Liability	Secured	Debt instruments	1173.83	6.65
Liability	Unsecured		2623.03	14.86

Table C.11: Composition of liabilities. Source: authors computations on supervisory data

Appendix D. Data references

Category	Classification	Type	Counterpart	Finrep reference
Asset	Non-tradable	Cash	Total	F_20.04_10_75 - F_20.04_11_75
Asset	Non-tradable	Debt instruments	Central bank	F_20.04_10_90 - F_20.04_11_90
Asset	Non-tradable	Debt instruments	Credit institutions	F_20.04_10_110 - F_20.04_11_110
Asset	Non-tradable	Debt instruments	Government	F_20.04_10_100 - F_20.04_11_100
Asset	Non-tradable	Debt instruments	Non-financial institutions	F_20.04_10_130 - F_20.04_11_130
Asset	Non-tradable	Debt instruments	Other financial institutions	F_20.04_10_120 - F_20.04_11_120
Asset	Non-tradable	Debt instruments	Total	F_20.04_10_80 - F_20.04_11_80
Asset	Non-tradable	Derivatives	Credit institutions	F_20.04_10_20 - F_20.04_11_20
Asset	Non-tradable	Derivatives	Other financial institutions	F_20.04_10_30 - F_20.04_11_30
Asset	Non-tradable	Derivatives	Total	F_20.04_10_10 - F_20.04_11_10
Asset	Non-tradable	Equity	Credit institutions	F_20.04_10_50 - F_20.04_11_50
Asset	Non-tradable	Equity	Non-financial institutions	F_20.04_10_70 - F_20.04_11_70
Asset	Non-tradable	Equity	Other financial institutions	F_20.04_10_60 - F_20.04_11_60
Asset	Non-tradable	Equity	Total	F_20.04_10_40 - F_20.04_11_40
Asset	Non-tradable	Loans	Central bank	F_20.04_10_150 - F_20.04_11_150
Asset	Non-tradable	Loans	Credit institutions	F_20.04_10_170 - F_20.04_11_170
Asset	Non-tradable	Loans	Government	F_20.04_10_160 - F_20.04_11_160
Asset	Non-tradable	Loans	Households	F_20.04_10_220 - F_20.04_11_220
Asset	Non-tradable	Loans	Non-financial institutions	F_20.04_10_190 - F_20.04_11_190
Asset	Non-tradable	Loans	Other financial institutions	F_20.04_10_180 - F_20.04_11_180
Asset	Non-tradable	Loans	Total	F_20.04_10_140 - F_20.04_11_140
Asset	Tradable	Debt instruments	Central bank	F_20.04_11_90
Asset	Tradable	Debt instruments	Credit institutions	F_20.04_11_110
Asset	Tradable	Debt instruments	Government	F_20.04_11_100
Asset	Tradable	Debt instruments	Non-financial institutions	F_20.04_11_130
Asset	Tradable	Debt instruments	Other financial institutions	F_20.04_11_120
Asset	Tradable	Debt instruments	Total	F_20.04_11_80
Asset	Tradable	Derivatives	Credit institutions	F_20.04_11_20
Asset	Tradable	Derivatives	Other financial institutions	F_20.04_11_30
Asset	Tradable	Derivatives	Total	F_20.04_11_10
Asset	Tradable	Equity	Credit institutions	F_20.04_11_50
Asset	Tradable	Equity	Non-financial institutions	F_20.04_11_70
Asset	Tradable	Equity	Other financial institutions	F_20.04_11_60
Asset	Tradable	Equity	Total	F_20.04_11_40
Asset	Tradable	Loans	Central bank	F_20.04_11_150
Asset	Tradable	Loans	Credit institutions	F_20.04_11_170
Asset	Tradable	Loans	Government	F_20.04_11_160
Asset	Tradable	Loans	Households	F_20.04_11_220
Asset	Tradable	Loans	Non-financial institutions	F_20.04_11_190
Asset	Tradable	Loans	Other financial institutions	F_20.04_11_180
Asset	Tradable	Loans	Total	F_20.04_11_140

Table D.1: Finrep references for assets

Category	Type	Counterpart	Finrep reference					
Liabilities	Debt instruments	Central bank	F_08.01.a_10_60	F_08.01.a_20_60	F_08.01.a_30_60	F_08.01.a_34_60	F_08.01.a_35_60	F_08.01.a_37_60
Liabilities	Deposits	Credit institutions	F_08.01.a_10_170	F_08.01.a_20_170	F_08.01.a_30_170	F_08.01.a_34_170	F_08.01.a_35_170	F_08.01.a_37_170
			F_08.01.a_10_190	F_08.01.a_20_190	F_08.01.a_30_190	F_08.01.a_34_190	F_08.01.a_35_190	F_08.01.a_37_190
Liabilities	Debt Instruments (secured)		F_08.01.a_10_370	F_08.01.a_20_370	F_08.01.a_30_370	F_08.01.a_34_370	F_08.01.a_35_370	F_08.01.a_37_370
			F_08.01.a_10_380	F_08.01.a_20_380	F_08.01.a_30_380	F_08.01.a_34_380	F_08.01.a_35_380	F_08.01.a_37_380
			F_08.01.a_10_390	F_08.01.a_20_390	F_08.01.a_30_390	F_08.01.a_34_390	F_08.01.a_35_390	F_08.01.a_37_390
			F_08.01.a_10_400	F_08.01.a_20_400	F_08.01.a_30_400	F_08.01.a_34_400	F_08.01.a_35_400	F_08.01.a_37_400
Liabilities	Deposits	Government	F_08.01.a_10_110	F_08.01.a_20_110	F_08.01.a_30_110	F_08.01.a_34_110	F_08.01.a_35_110	F_08.01.a_37_110
Liabilities	Deposit with agreed maturity	Households	F_08.01.a_10_330	F_08.01.a_20_330	F_08.01.a_30_330	F_08.01.a_34_330	F_08.01.a_35_330	F_08.01.a_37_330
Liabilities	Deposits	Households	F_08.01.a_10_320	F_08.01.a_20_320	F_08.01.a_30_320	F_08.01.a_34_320	F_08.01.a_35_320	F_08.01.a_37_320
			F_08.01.a_10_340	F_08.01.a_20_340	F_08.01.a_30_340	F_08.01.a_34_340	F_08.01.a_35_340	F_08.01.a_37_340
Liabilities	Deposits	Non-financial corporations	F_08.01.a_10_270	F_08.01.a_20_270	F_08.01.a_30_270	F_08.01.a_34_270	F_08.01.a_35_270	F_08.01.a_37_270
			F_08.01.a_10_290	F_08.01.a_20_290	F_08.01.a_30_290	F_08.01.a_34_290	F_08.01.a_35_290	F_08.01.a_37_290
Liabilities	Other		F_08.01.a_10_10	F_08.01.a_20_10	F_08.01.a_30_10	F_08.01.a_34_10	F_08.01.a_35_10	F_08.01.a_37_10
			F_08.01.a_10_20	F_08.01.a_20_20	F_08.01.a_30_20	F_08.01.a_34_20	F_08.01.a_35_20	F_08.01.a_37_20
			F_08.01.a_10_440	F_08.01.a_20_440	F_08.01.a_30_440	F_08.01.a_34_440	F_08.01.a_35_440	F_08.01.a_37_440
Liabilities	Deposits	Other financial corporations	F_08.01.a_10_220	F_08.01.a_20_220	F_08.01.a_30_220	F_08.01.a_34_220	F_08.01.a_35_220	F_08.01.a_37_220
			F_08.01.a_10_240	F_08.01.a_20_240	F_08.01.a_30_240	F_08.01.a_34_240	F_08.01.a_35_240	F_08.01.a_37_240
Liabilities	Repo		F_08.01.a_10_200	F_08.01.a_20_200	F_08.01.a_30_200	F_08.01.a_34_200	F_08.01.a_35_200	F_08.01.a_37_200
			F_08.01.a_10_250	F_08.01.a_20_250	F_08.01.a_30_250	F_08.01.a_34_250	F_08.01.a_35_250	F_08.01.a_37_250
			F_08.01.a_10_300	F_08.01.a_20_300	F_08.01.a_30_300	F_08.01.a_34_300	F_08.01.a_35_300	F_08.01.a_37_300
			F_08.01.a_10_350	F_08.01.a_20_350	F_08.01.a_30_350	F_08.01.a_34_350	F_08.01.a_35_350	F_08.01.a_37_350
Liabilities	Unsecured		F_08.01.a_10_180	F_08.01.a_20_180	F_08.01.a_30_180	F_08.01.a_34_180	F_08.01.a_35_180	F_08.01.a_37_180
			F_08.01.a_10_230	F_08.01.a_20_230	F_08.01.a_30_230	F_08.01.a_34_230	F_08.01.a_35_230	F_08.01.a_37_230
			F_08.01.a_10_280	F_08.01.a_20_280	F_08.01.a_30_280	F_08.01.a_34_280	F_08.01.a_35_280	F_08.01.a_37_280
			F_08.01.a_10_410	F_08.01.a_20_410	F_08.01.a_30_410	F_08.01.a_34_410	F_08.01.a_35_410	F_08.01.a_37_410

Table D.2: Finrep references for Liabilities

Percentage of encumbrance of total assets and collateral by type	
Loans on demand	(F 32.01_020_010 + F 32.02.a_140_010) / (F 32.01_020_060 + F 32.01_020_010 + F 32.02.a_140_040 + F 32.02.a_140_010)
Equity instruments	(F 32.01_030_010 + F 32.02.a_150_010) / (F 32.01_030_060 + F 32.01_030_010 + F 32.02.a_150_040 + F 32.02.a_150_010)
Debt securities	(F 32.01_040_010 + F 32.02.a_160_010) / (F 32.01_040_060 + F 32.01_040_010 + F 32.02.a_160_040 + F 32.02.a_160_010)
Loans and advances other than loans on demand	(F 32.01_100_010 + F 32.02.a_220_010) / (F 32.01_100_060 + F 32.01_100_010 + F 32.02.a_220_040 + F 32.02.a_220_010)
Other assets	(F 32.01_120_010 + F 32.02.a_230_010) / (F 32.01_120_060 + F 32.01_120_010 + F 32.02.a_230_040 + F 32.02.a_230_010)
Total	(F 32.01_010_010 + F 32.02.a_130_010) / (F 32.01_010_060 + F 32.01_010_010 + F 32.02.a_130_040 + F 32.02.a_130_010)

Table D.3: References for share of encumbered assets. Source (consulted on 19.02.2023): EBA report on encumbrance, July 2021. (Fig. 8). Available here: `https://www.eba.europa.eu/sites/default/documents/files/document_library/Risk%20Analysis%20and%20Data/Risk%20Assessment%20Reports/2021/1017618/Report%20on%20Asset%20Encumbrance.pdf`

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